Supernova neutrinos: shocking physics, revisited

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Topics in Cosmic Neutrino Physics

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Basic setup: A gravity-powered neutrino bomb

- Chandrasekhar: an object with mass greater than $\sim 1.4\, M_\odot$ cannot support itself against gravitational collapse by degeneracy pressure
  - Electrons near Fermi surface become relativistic and EOS becomes unstable to collapse. In natural units, the criterion is $M_* \sim M_{Pl}^3/M_N^2 \sim M_\odot$ (!!).
- Central Fe core ($\sim 1.4\, M_\odot$) collapses reaching v ~c/4, until nuclear densities,
  - 10^{10} g/cm^3 $\rightarrow$ 10^{14} g/cm^3
- The resulting protoneutron star (~ a few * 10 km in radius) traps neutrinos. The binding energy $G_N M^2/R$ is stored mostly in the Fermi seas of electrons & electron neutrinos
- Neutrinos diffuse out on the time scale of a few seconds: $t \sim R^2/c\lambda \sim 1$ s
  - carry away > 99% of all released gravitational energy.
  - Approximately 0.15 M_{SUN} is converted into a burst of ~10 MeV neutrinos
  - 10^{58} neutrinos in a few seconds is definitely intensity frontier!

Basic setup: Visible explosion

- The inner core remains subsonic, while the outer core is falling at supersonic speeds. On the boundary, a shock front is formed, first inside the neutrinosphere.
- It moves out, breaks through the neutrinosphere, then loses energy to neutrino emission and disintegration of Iron.
- The shock stalls at ~ 200 km. Complicated interplay between volume energy loss and gain from streaming neutrinos on the bottom: vigorous convection.
- The shock revives during ~1 sec. Blows off the rest of the star with energy of about 10^{51} ergs, about the binding energy of the envelope. This gives rise to a visible explosion.

Stages of the explosion

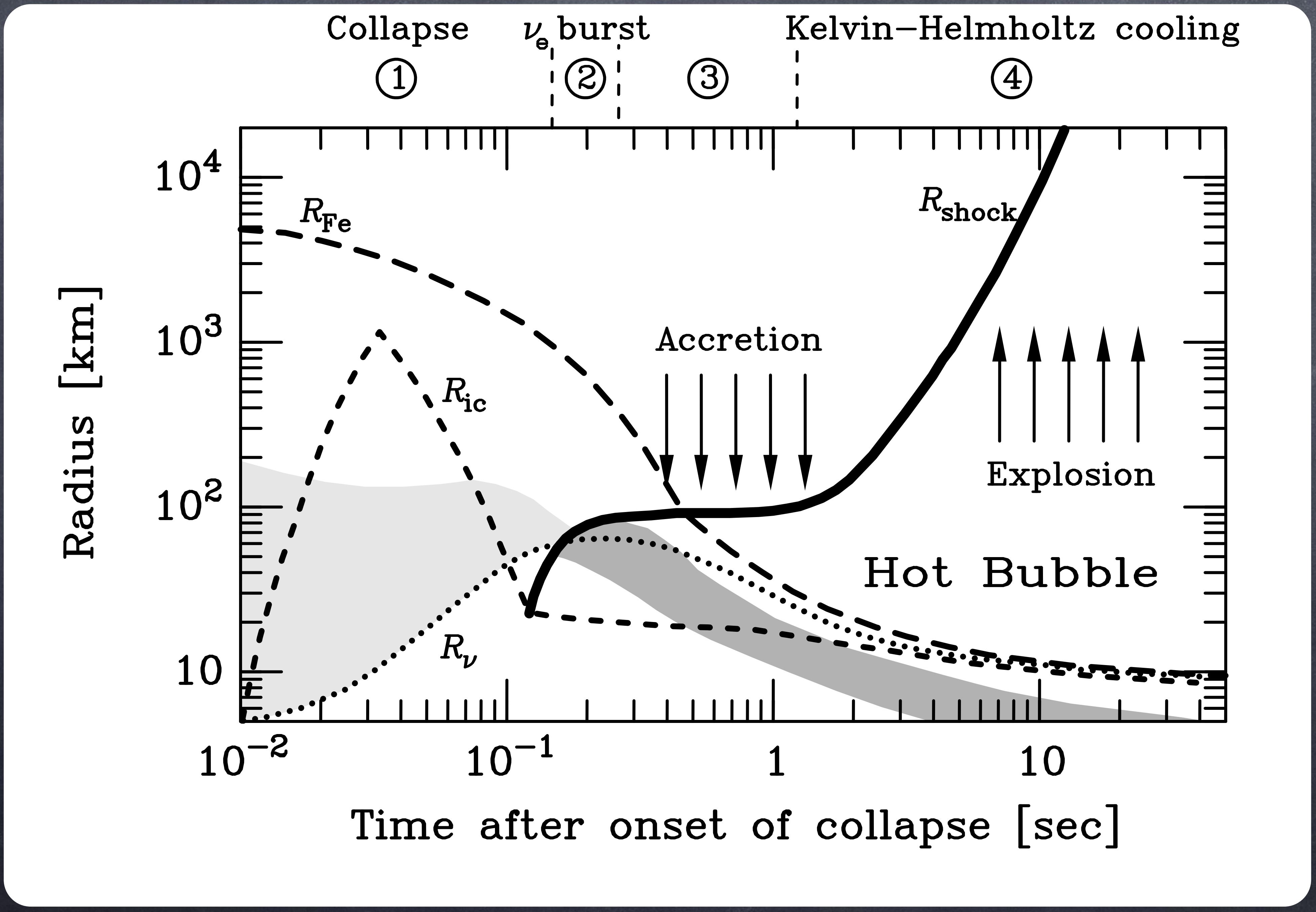
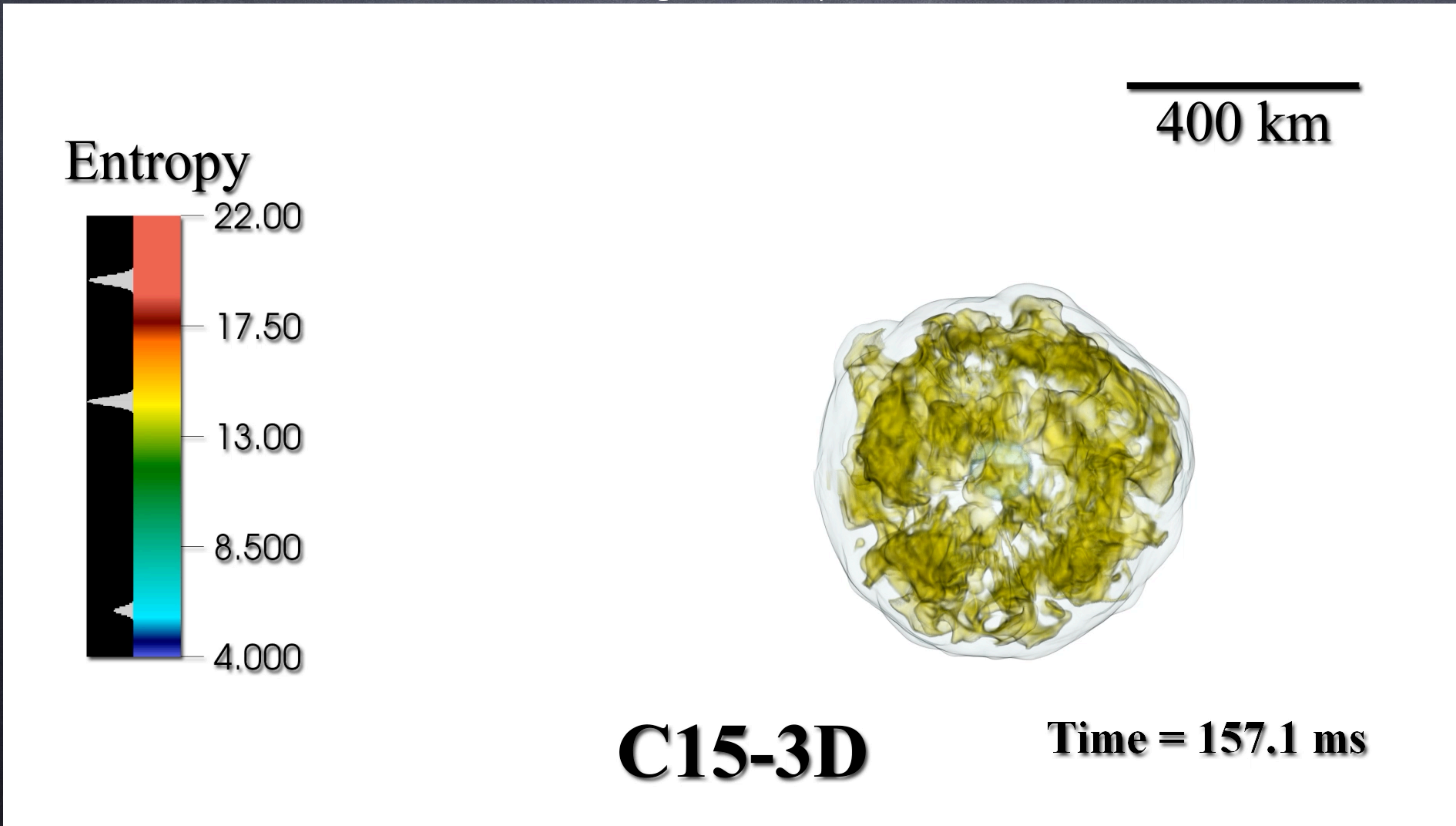
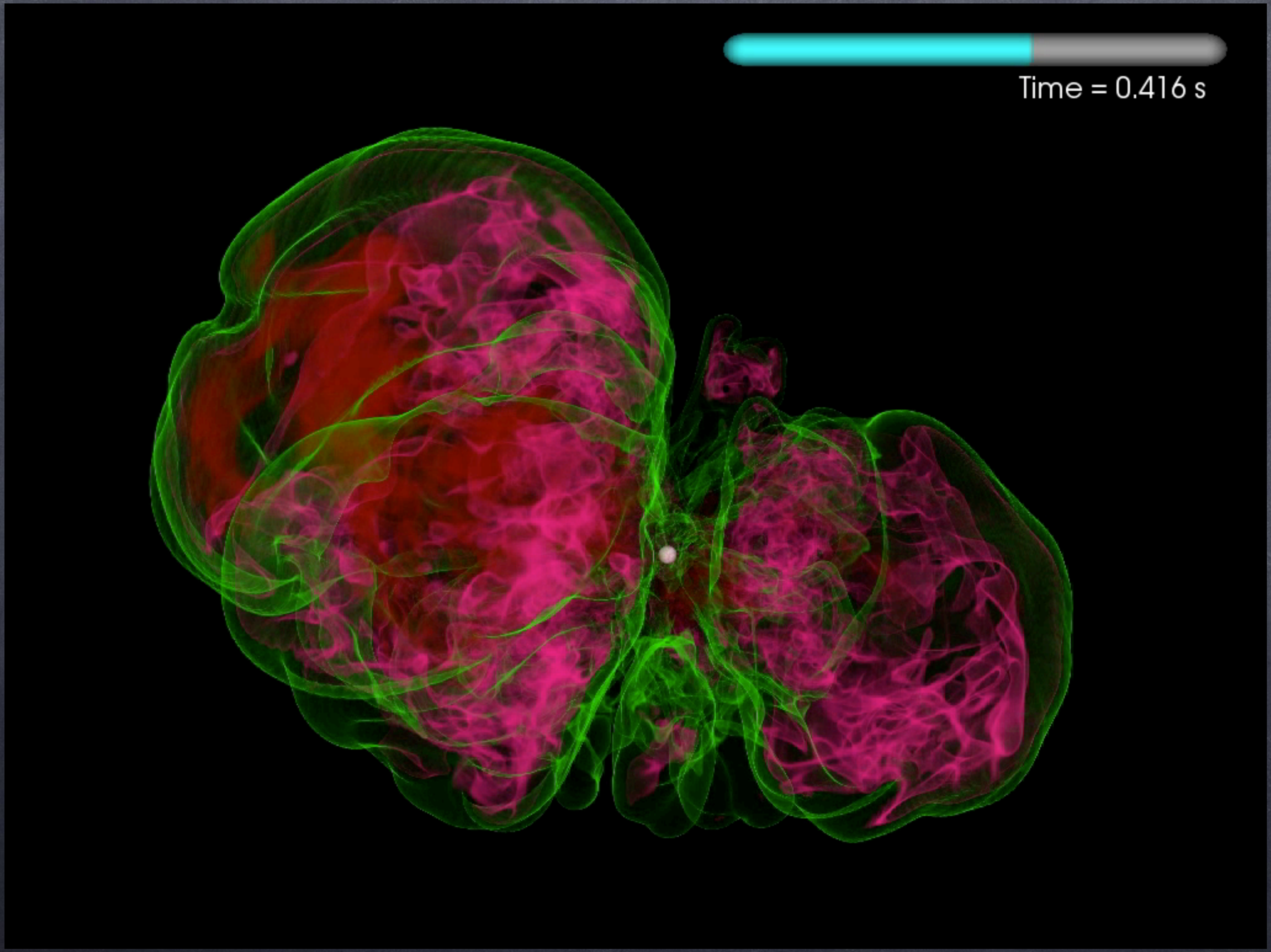


Fig. credit: T. Janka & G. Raffelt

Modern 3D simulations: ORNL group 2015



Modern 3D simulations: Princeton group 2018

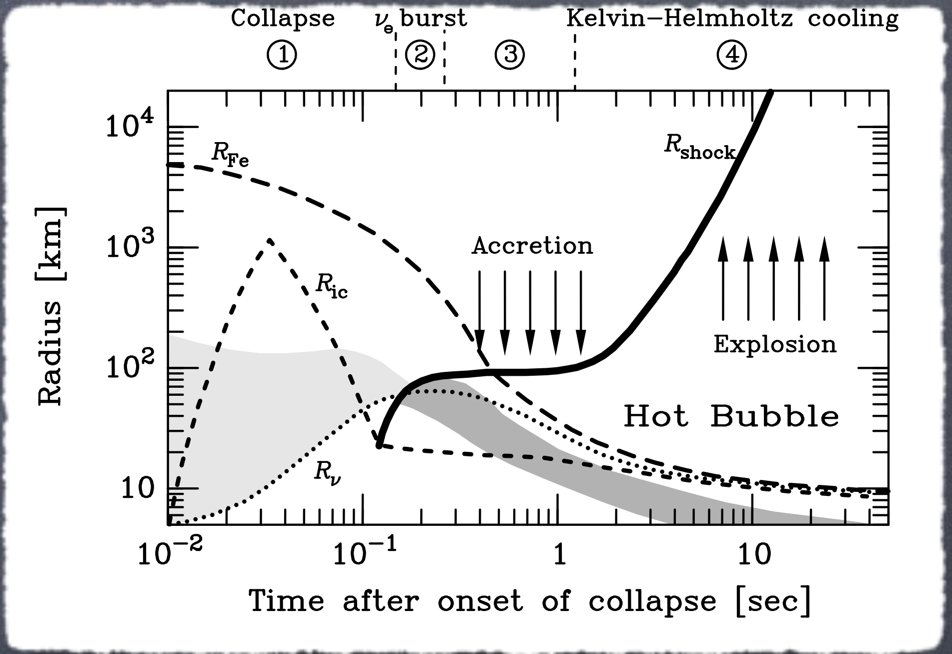


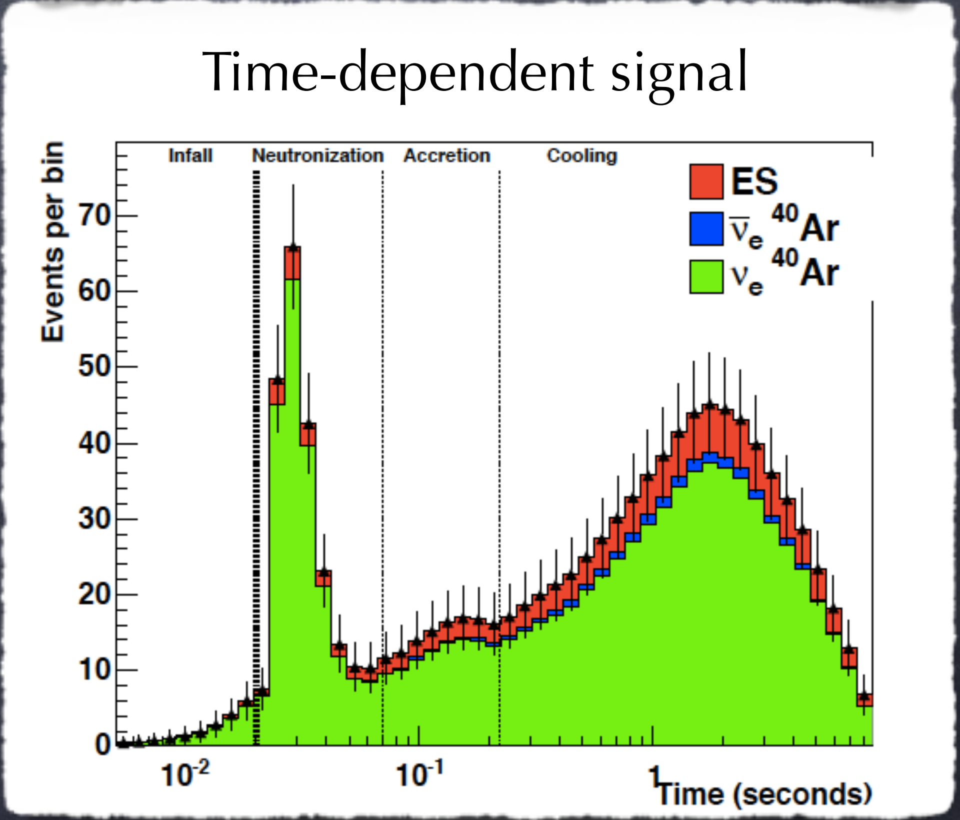
Basic setup: observations

- $G_N M_{core}^2 / R \sim 10^{53}$ erg emitted in a burst of 10^7 eV neutrinos, roughly equipartitioned between flavors -> $10^{57}\ \nu_e$
- Assuming $l \sim 8\ kpc$, expected fluence on Earth is $\sim 1.4 \times 10^{11}\ cm^{-2}$
- CC cross section on Ar $\sim G_F^2 E_\nu^2 \sim 10^{-40}\ cm^2$; 40 kt detector has 10^6 moles of Ar
- Number of interactions
  $\sim (10^{-40}\ cm^2)\ (1.4 \times 10^{11}\ cm^{-2})\ (6 \times 10^{23} \times 10^6) \sim 8 \times 10^3$
- Details depend on the distance to the SN ($\propto l^{-2}$), emitted energy spectra, progenitor mass, flavor oscillations, etc
- But the main point is that a galactic core-collapse supernova will create many thousands of ν_e interactions in the DUNE far detector
  - And $\sim 10^4 - 10^5\ \bar{\nu}_e$ events in Super/HyperK.

Refresher: What's the goal here?

- With such high statistics, it will be possible to study not only the total burst signal, but to track its time evolution second by second
- Need to know how to read this signal and what to look for

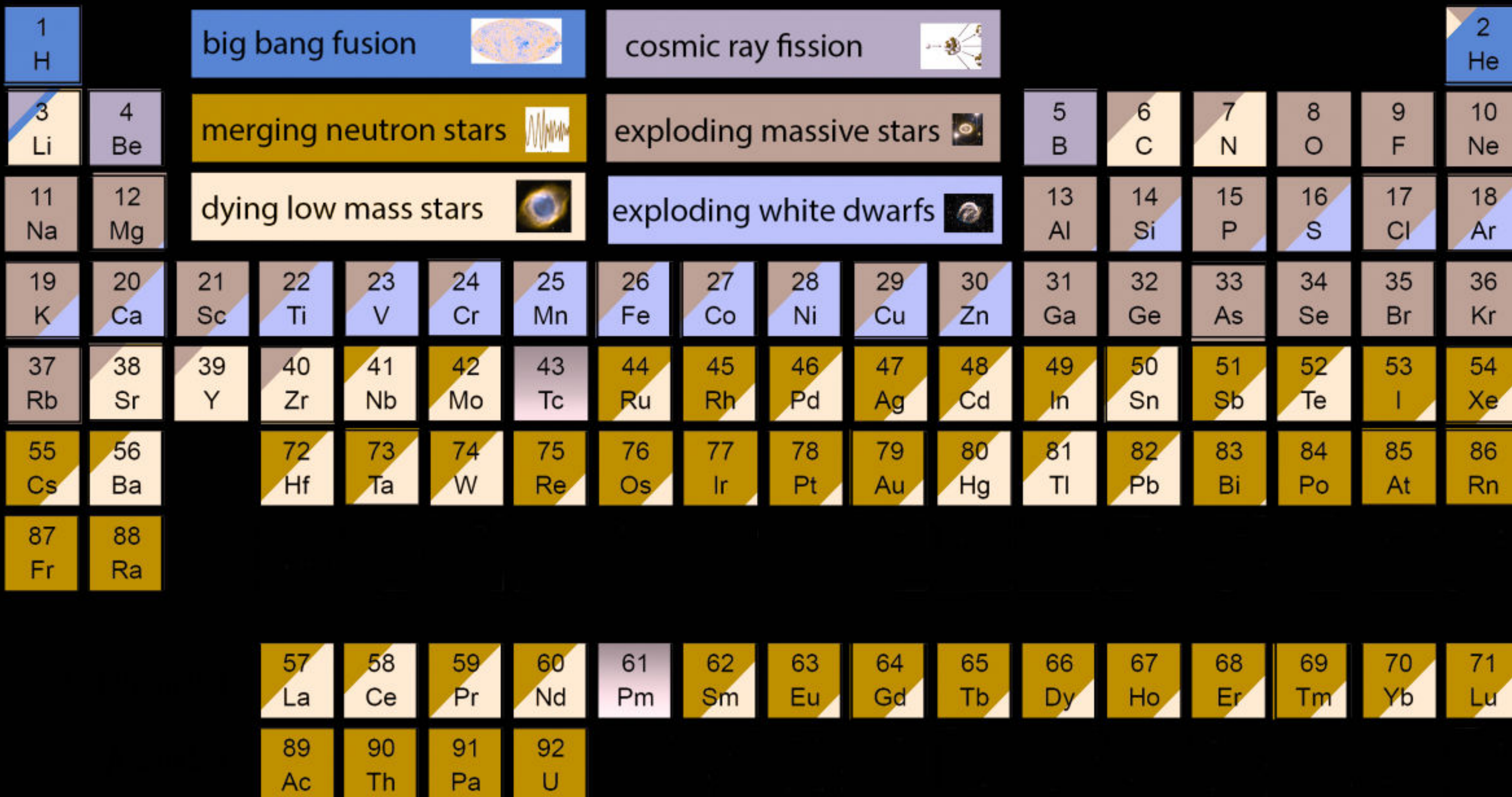




Why should we care? “Theory of everything”!

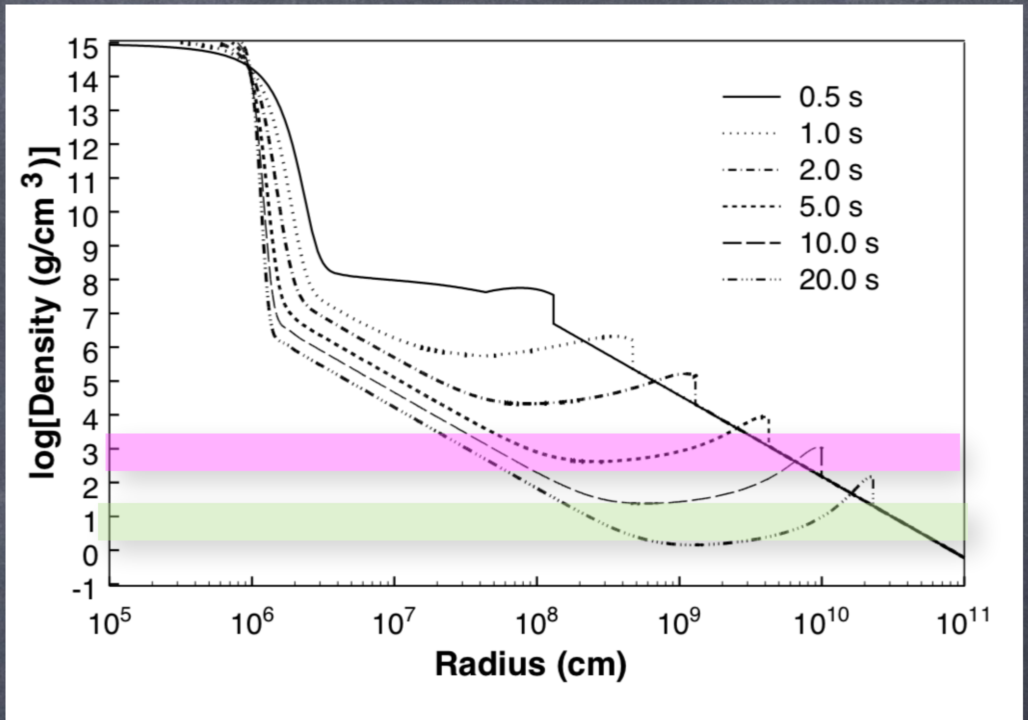
- Conditions not reproducible on Earth make them unique laboratories for particle and nuclear physics
  - From axions, majorons, dark photons, etc, to EOS of nuclear matter, to collective flavor oscillations in dense neutrino gases
- The universe around us: Simulations of the galactic disk show that supernova feedback is crucial to its structure.
- Origin of stuff: Supernovae synthesize and disperse heavy elements.
  - BBN created hydrogen and helium. Chemical elements around us were once inside a star

The Origin of the Solar System Elements

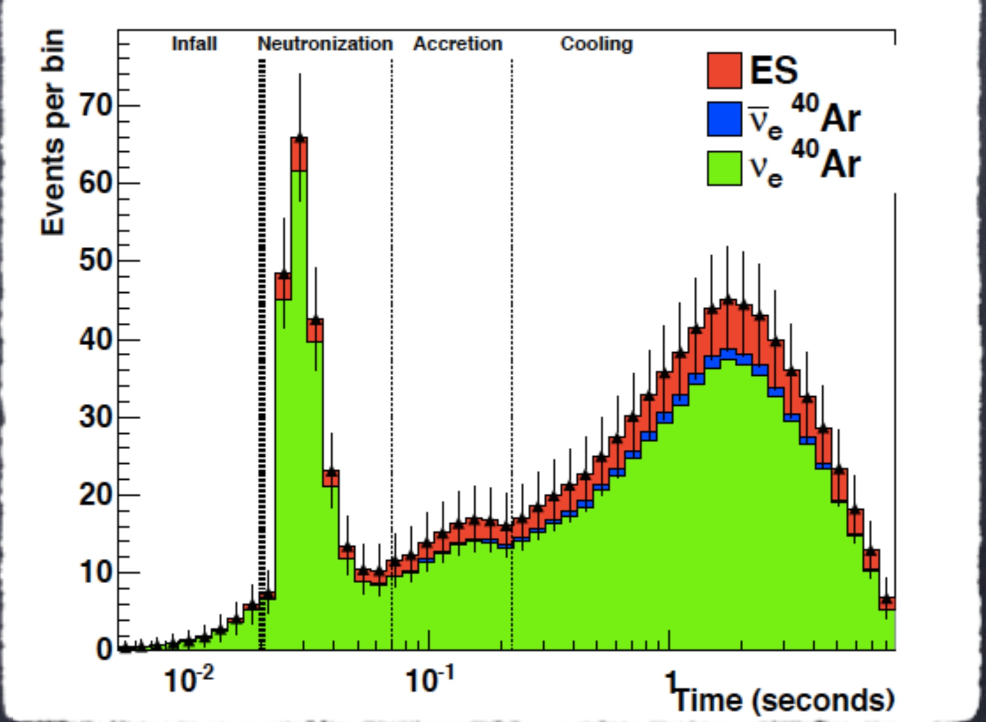


Flavor oscillations: not optional!

- Oscillations will imprint information from the inner regions of the explosion on the observed spectra
- We need to know (i) what to look for and (ii) how the detector performance will affect what can be seen

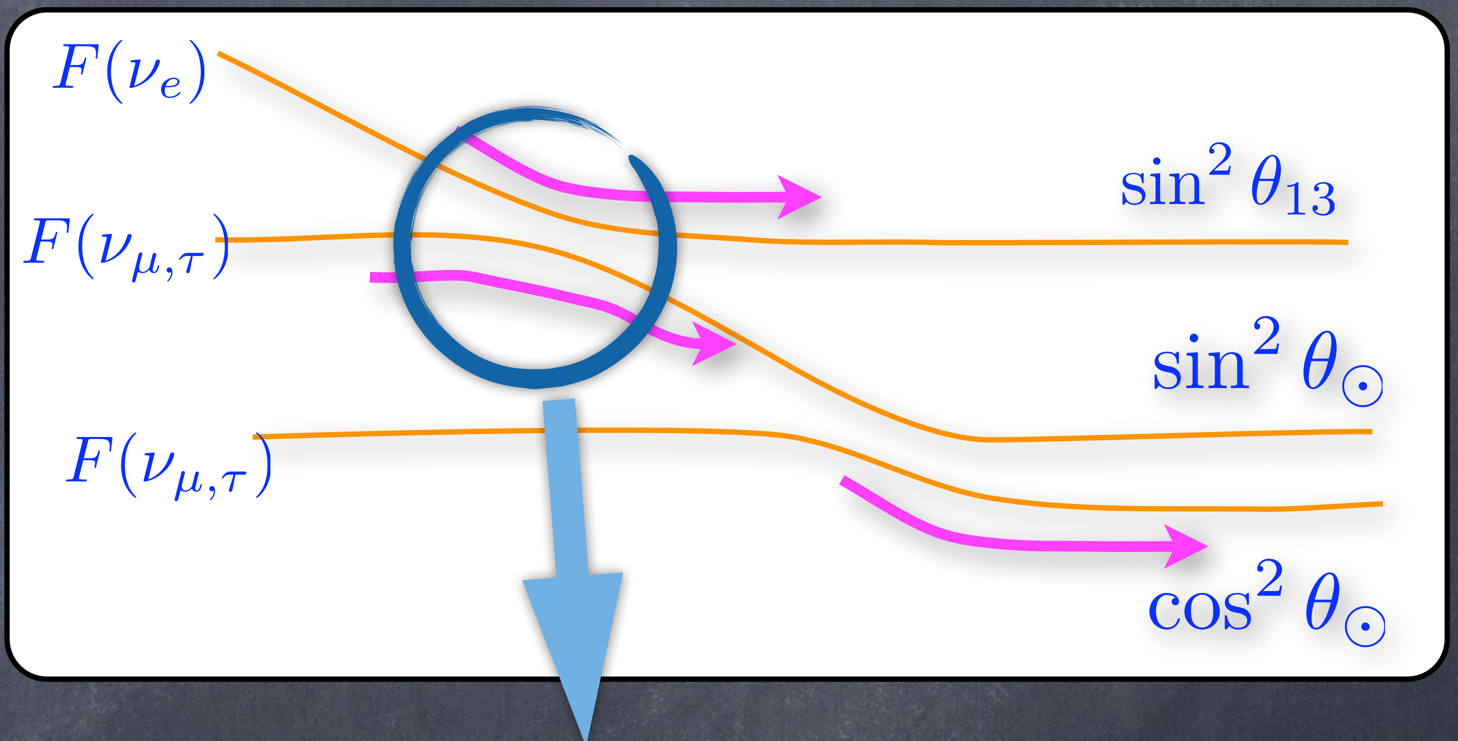


Time-dependent signal



MSW effects in SN

- Matter effect leads to adiabatic evolution of states in the Sun: measured!
- In SN, higher densities -> two resonance regions
- Using known masses and mixing angles, we can check that both are adiabatic in the progenitor profile
- $\lambda_{osc} \sim 6\ km$ for E=20 MeV, $\lambda_{profile} \sim 10^4\ km$, $\sin^2 2\theta_{13} \simeq 0.084$

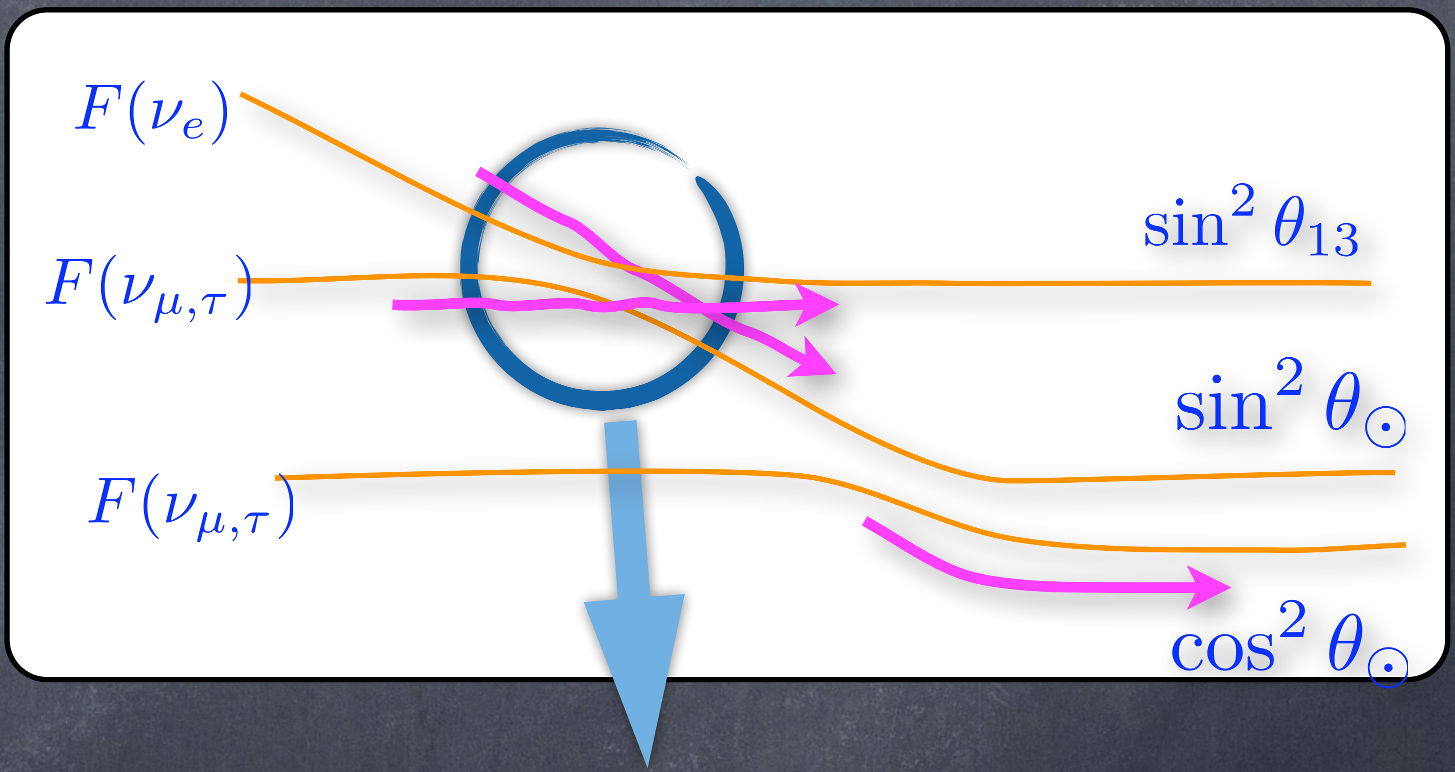


$$P_{jump} = \exp\left(-\frac{\pi(\Delta m^2/4E_\nu)\sin^2 2\theta}{|d\log n_e/dr|}\right)$$

$$P_{jump} = \exp\left(-\frac{\pi\lambda_{profile}}{\lambda_{osc}}\sin^2 2\theta_{13}\right)$$

MSW effects in SN

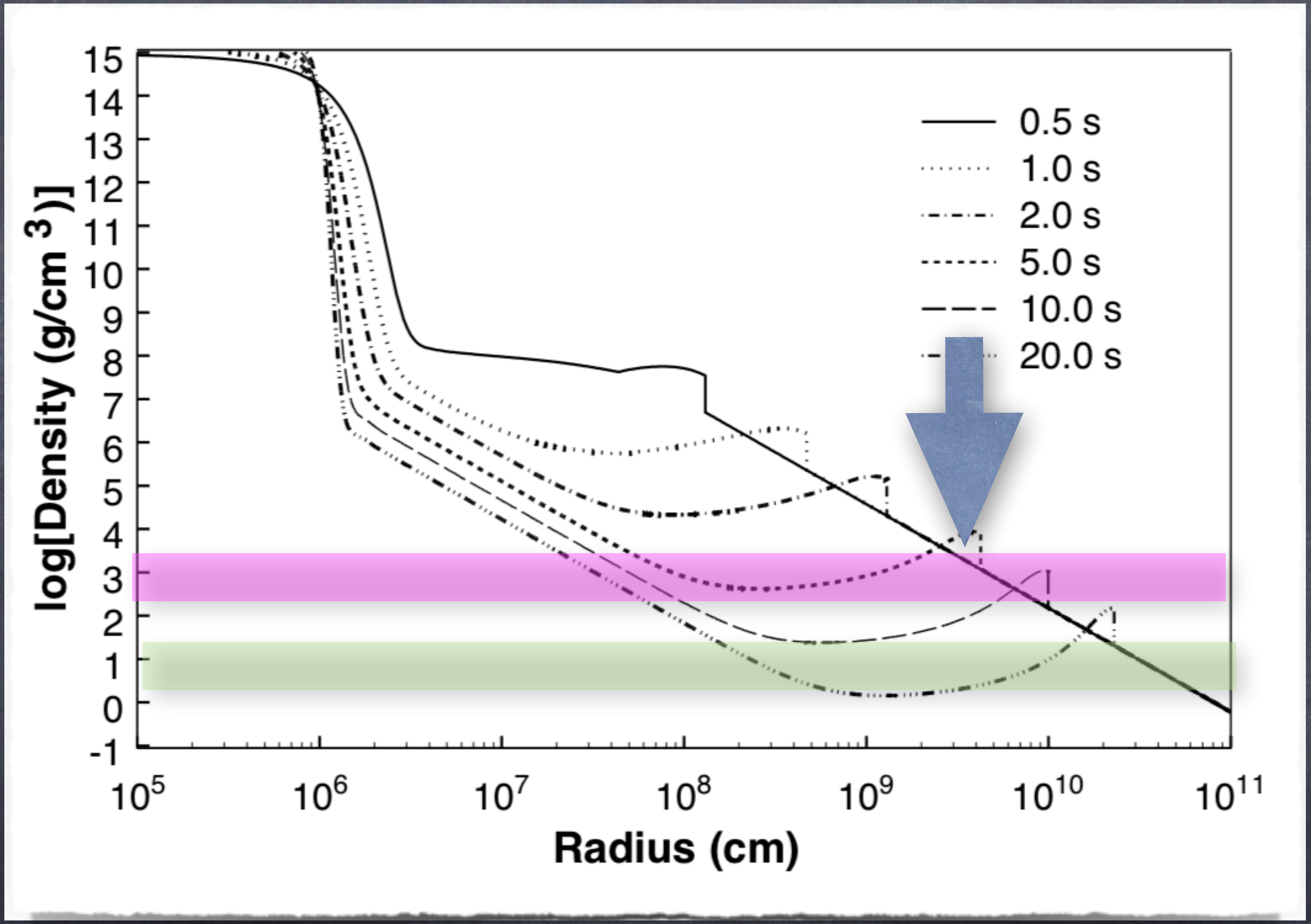
- The is infinitely thin compared to the neutrino oscillation length -> completely non-adiabatic
- Electron neutrinos, which before were swept into ν_3 now go into ν_2.
- ν_2 has a higher probability of being measured as ν_e than ν_3
  - $\sin^2\theta_{12}$ vs $\sin^2\theta_{13}$



$$P_{jump} = \exp\left(-\frac{\pi\lambda_{shock}}{\lambda_{osc}}\sin^2 2\theta_{13}\right)$$

-> If original ν_e flux was colder, observed flux gets colder

Oscillations imprint information



- R. Schirato and G. Fuller (2002): the relevant nonadiabatic feature is the expanding shock front

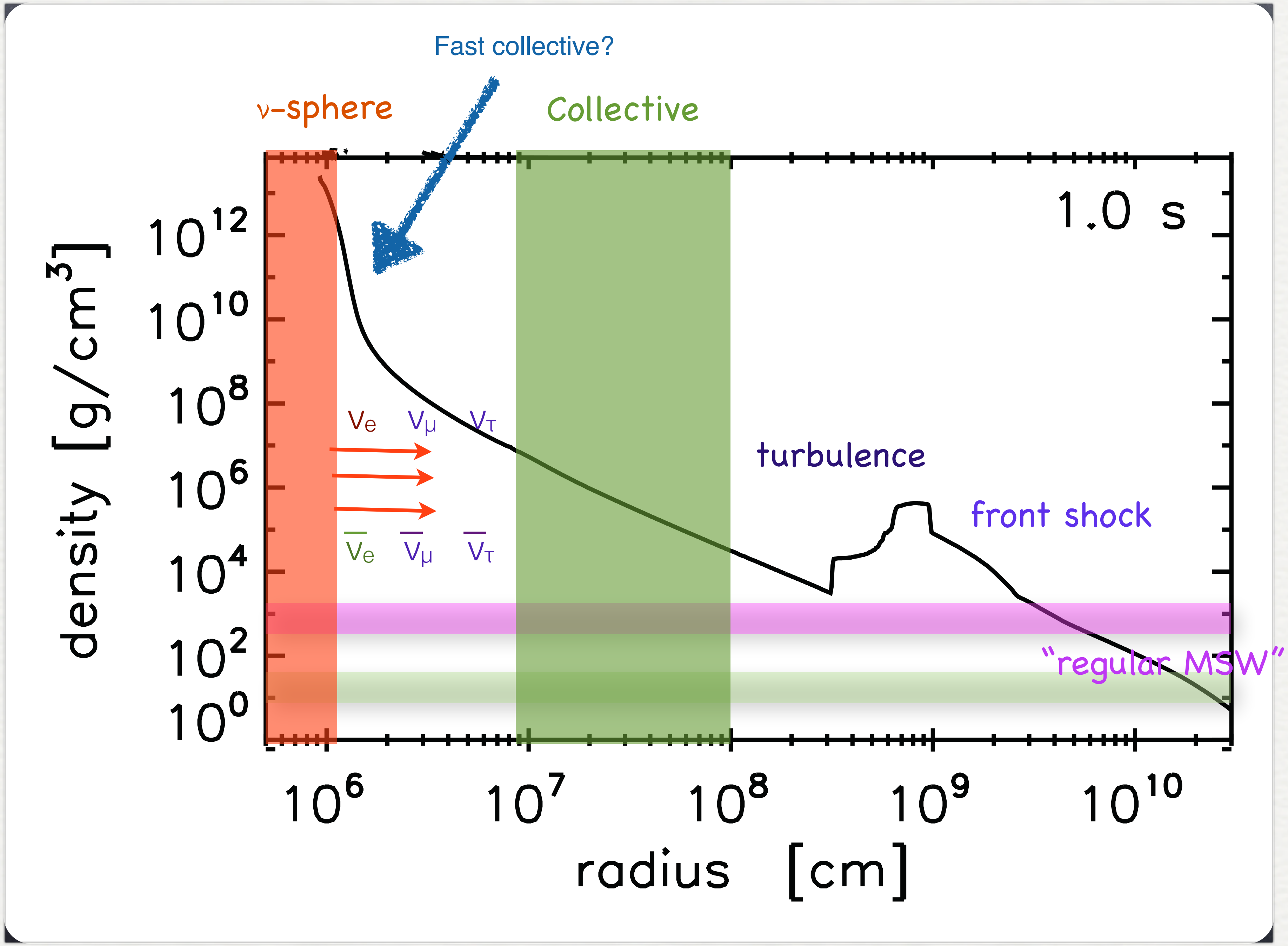
Good project for a grad student?

- Many things about SN flavor oscillations are complicated!
- This shock effect seems like one of the easier things that one could use to introduce students to the subject without "shocking" them right away
- … Of course, once you start looking closer, all sorts of interesting things might come up

Payel Mukhopadhyay

Stanford University

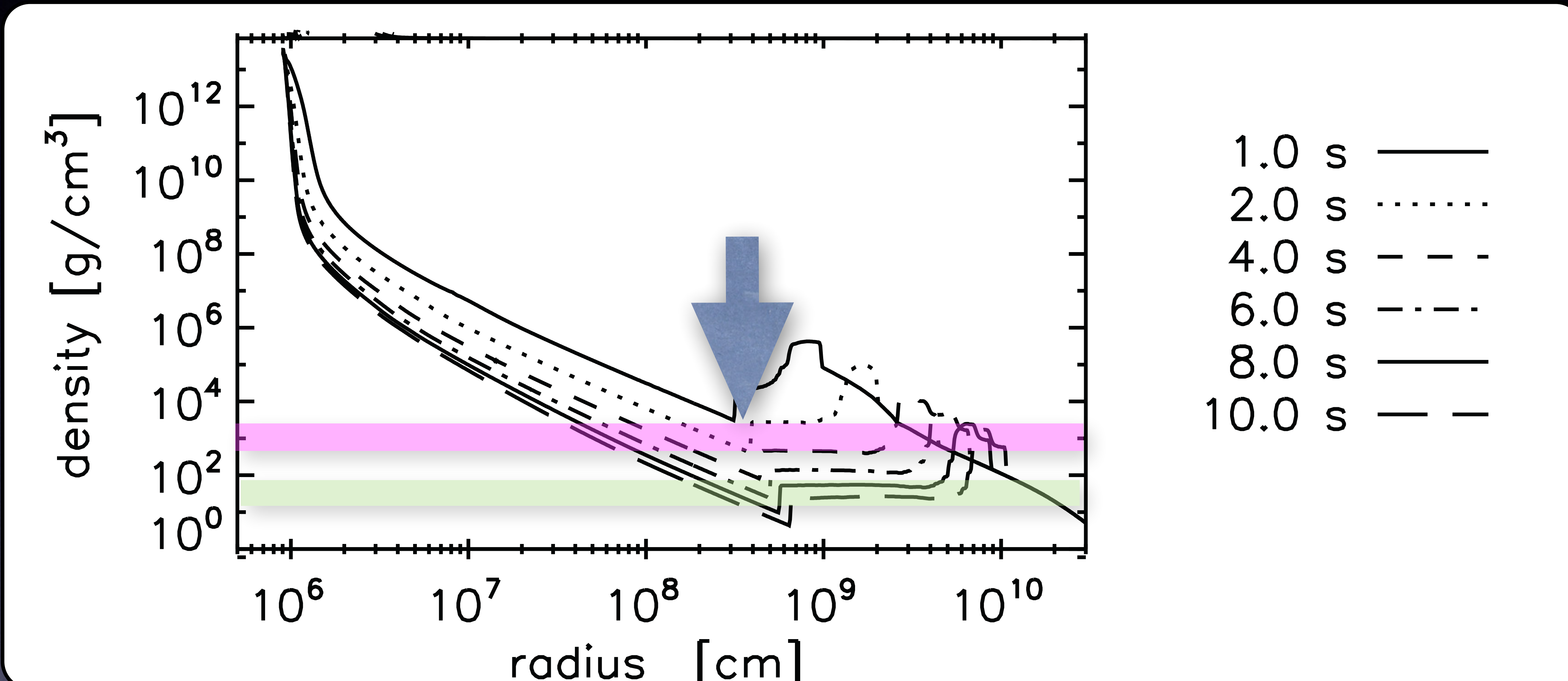
First, to model the signal, one has to take into account the full oscillation physics which is extremely rich



Different oscillation phenomena

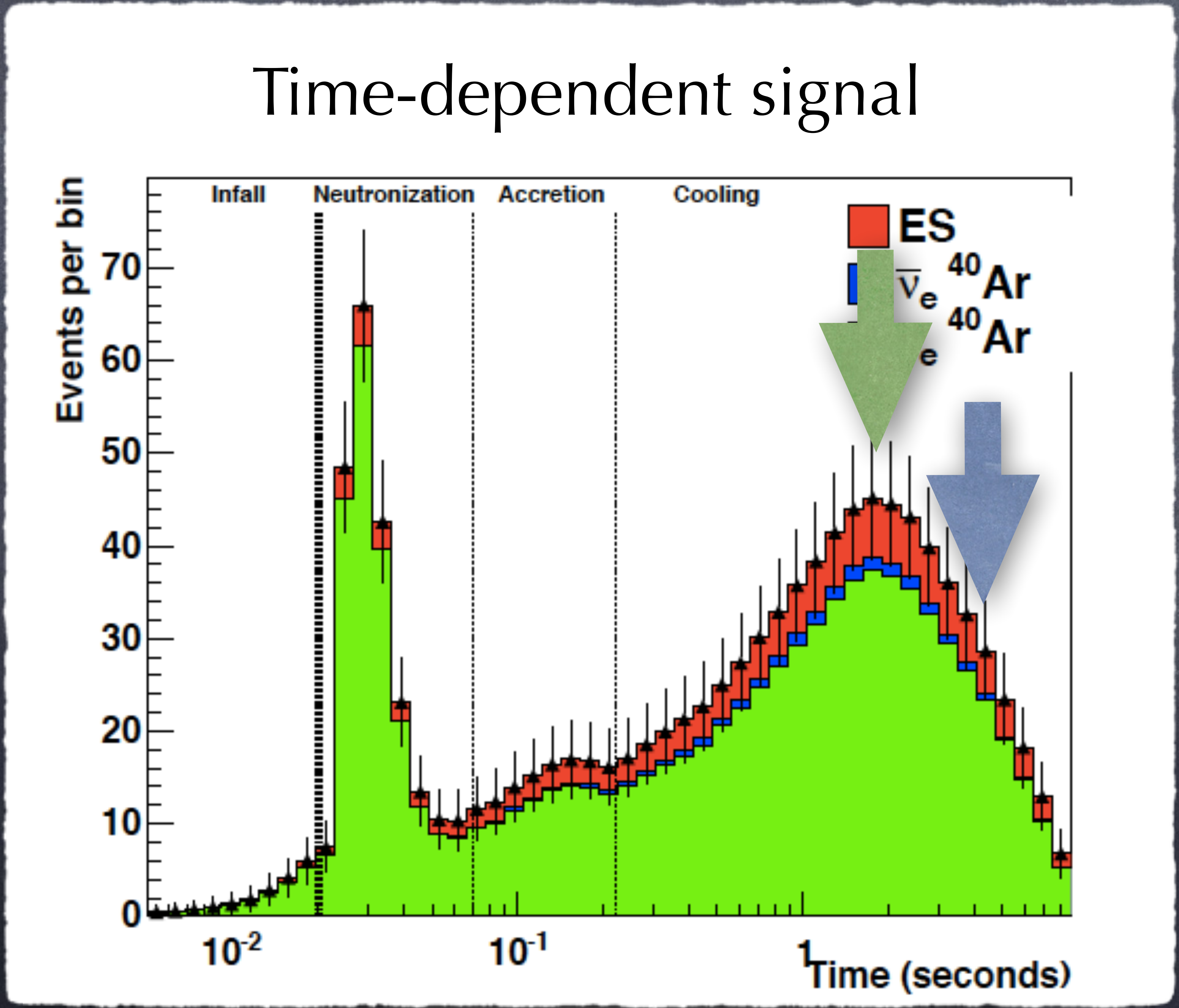
- Even if we don't focus on the other oscillation phenomena, we still need to reasonably include them
- The plan is to take a physically meaningful, representative calculation for each effect
- For turbulence, follow the approach of AF & A. Gruzinov, astro-ph/0607244: infer the amplitude of small-scale fluctuations using Kolmogorov cascade
  - Typical signature: time-dependent flavor depolarization
- For collective oscillations, do multi-angle, spherically symmetric calculations with spectra from modern simulations
  - Typical signature: high-energy spectral split
- For fast collective, see Huaiyu Duan's talk
  - Typical signature is unavailable as of today

What about matter profiles? Published simulations differ on density features!



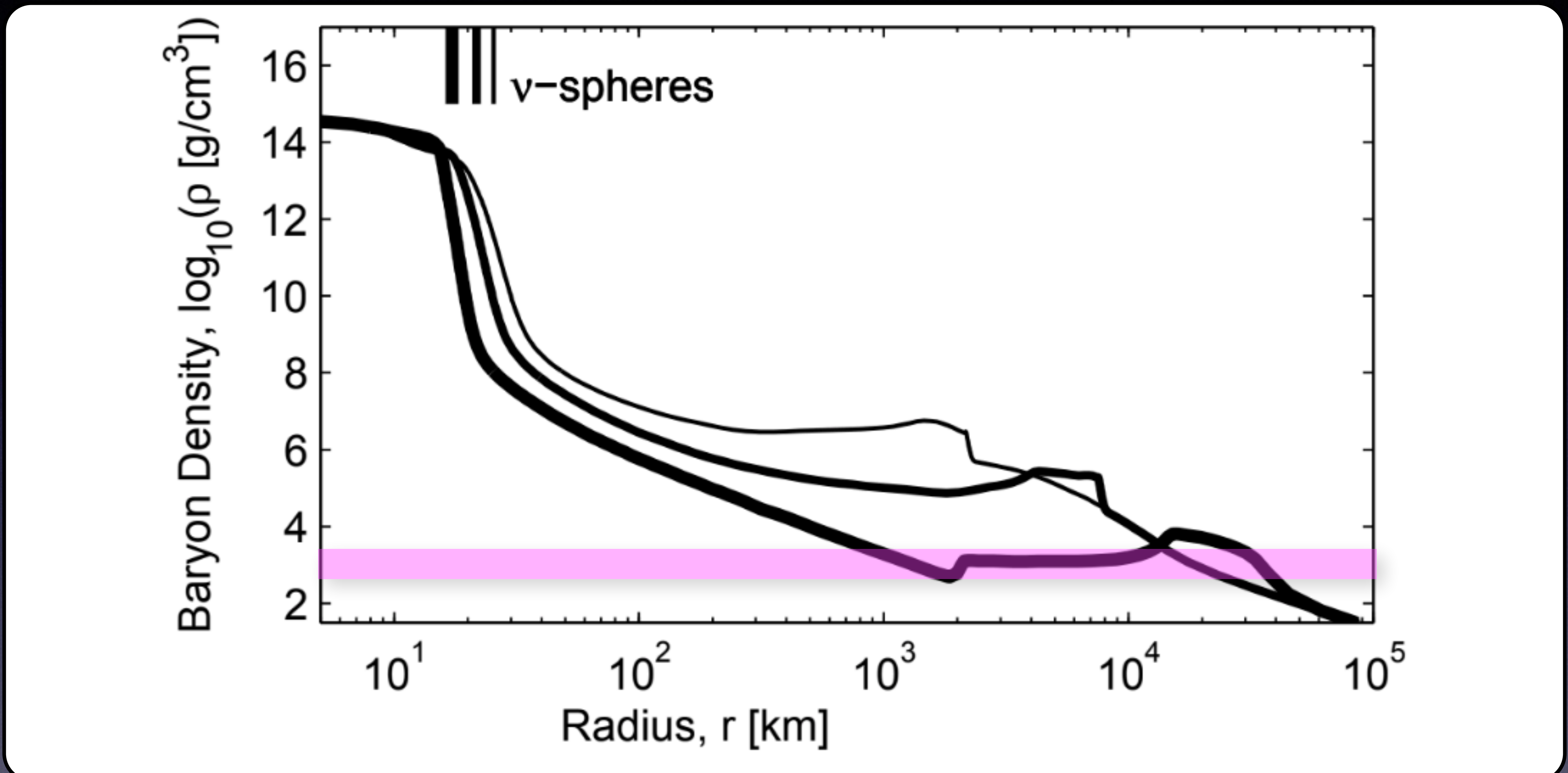
- Simulations by Arcones, Janka, and Scheck (2006)
- The most important feature is a termination shock of the neutrino-driven wind close to the proto-neutron star
- Impacts MSW earlier, at 2-3 seconds, when fluxes are higher

Timing



Time-dependent signal
Infall
Neutronization
Accretion
Cooling
ES
Events per bin
Time (seconds)

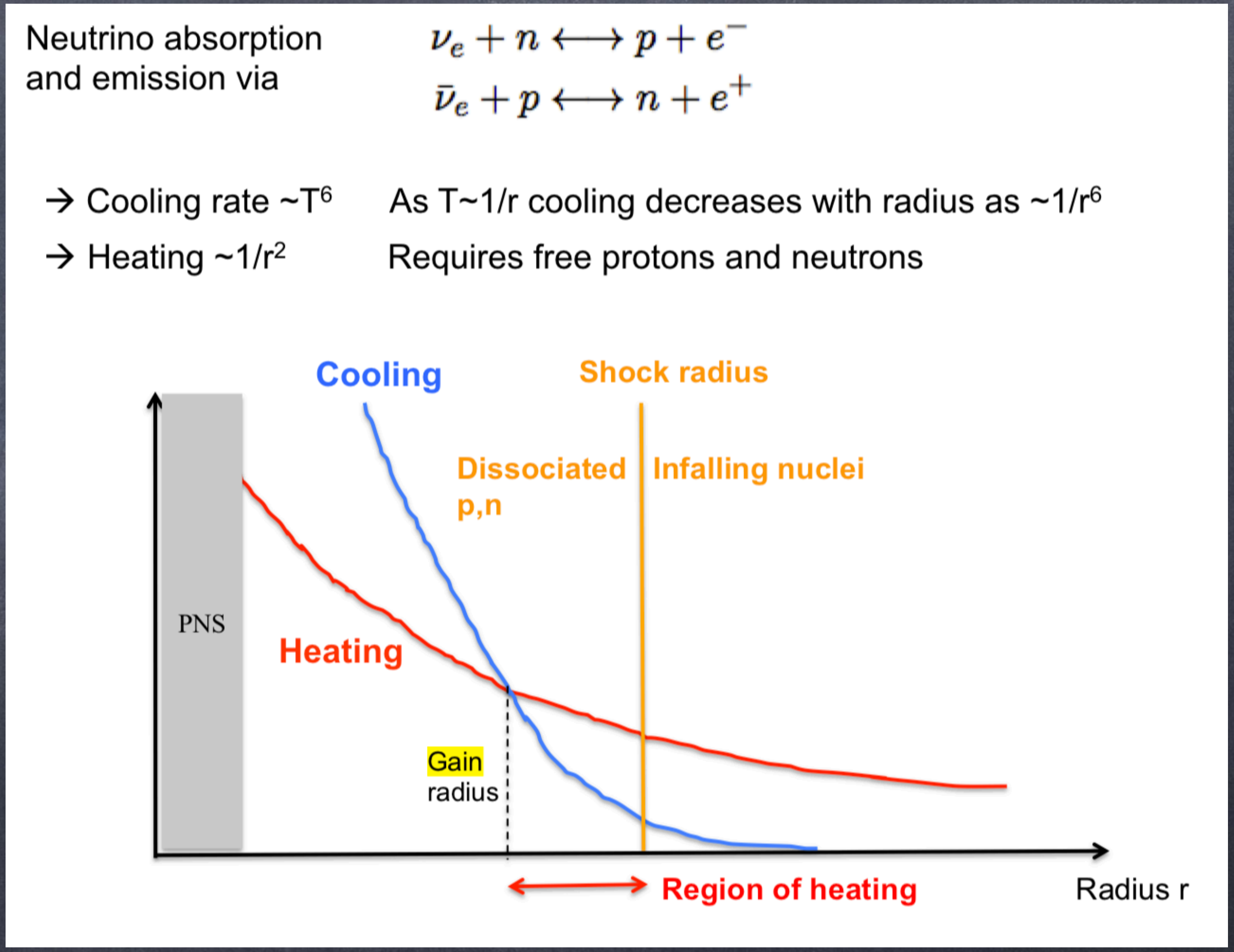
Yet another simulation



- Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer 0908.1871 [astro-ph.HE]
- The termination shock feature intermittent?
  - Absent at 1 second, present by 3 seconds. How is this possible?
  - The paper only says that they "agree with the others"

What's going on?

- Numerical artifacts? Real physics?
- To understand this, Payel Mukhopadhyay, we built our own physics model of the neutrino-driven outflow ("wind")
- This outflow is created when streaming neutrinos deposit energy above the neutrinosphere, outside of the "gain radius"



Nature of the outflow

- The material heated by neutrinos is then launched outwards and eventually runs into the expanding shell
- The question is whether it is accelerated to supersonic speeds (“wind”) or remains subsonic (“breeze”)
- Supersonic means termination shock, subsonic gives a smooth profile

Underlying equations

$$\rho v \frac{dv}{dr} = -\frac{dP}{dr} - \frac{GM\rho}{r^2}.$$

Pressure balance equation

$$S \equiv 4aT^3/3n_N$$

$$v_s^2 = \frac{TS}{3m_N}.$$

$$4\pi r^2 \rho v = \dot{M}, \quad \frac{d(r^2\rho v)}{dr} = 0.$$

Mass Conservation

$$\left(v - \frac{v_s^2}{v}\right)\frac{dv}{dr} = \frac{2v_s^2}{r} - \frac{GM}{r^2} - \frac{\dot{q}}{3v}.,$$

$$\dot{q} = v\frac{d}{dr}\left(\frac{v^2}{2} + 3v_s^2 - \frac{GM}{r}\right).,$$

$$v\frac{dS}{dr} = \frac{\dot{q}m_N}{T}.$$

$$\frac{d(4\pi r^2 v(4aT^3/3))}{dr} = \frac{L_\nu \sigma n}{T}.$$

Entropy generation

Physical conditions in the outflow: Density dominated by baryons, pressure dominated by radiation.

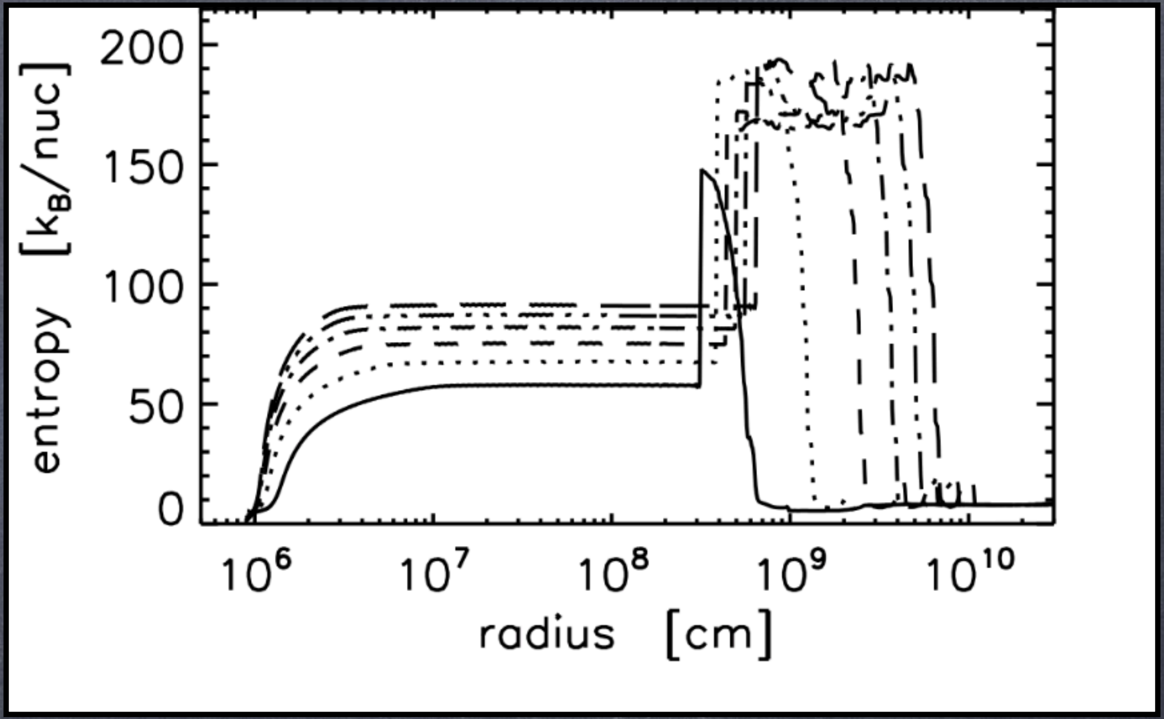
Hydrodynamic equations are known (Duncan et al, Qian & Woosley), but, somehow, the physical boundary conditions have not been systematically treated.

What do I mean by that?

- Duncan, Shapiro and Wasserman (1986) treat the outflow following the framework for stellar winds, which expand in practically empty space and always reach supersonic speeds.
- But the neutrino-driven wind in a SN runs into the back of the expanding material!
- For sufficiently high density of this material, the outflow can be “quenched”, never reaching the speed of sound. In this case, the entire flow is causally connected.

A few technical points

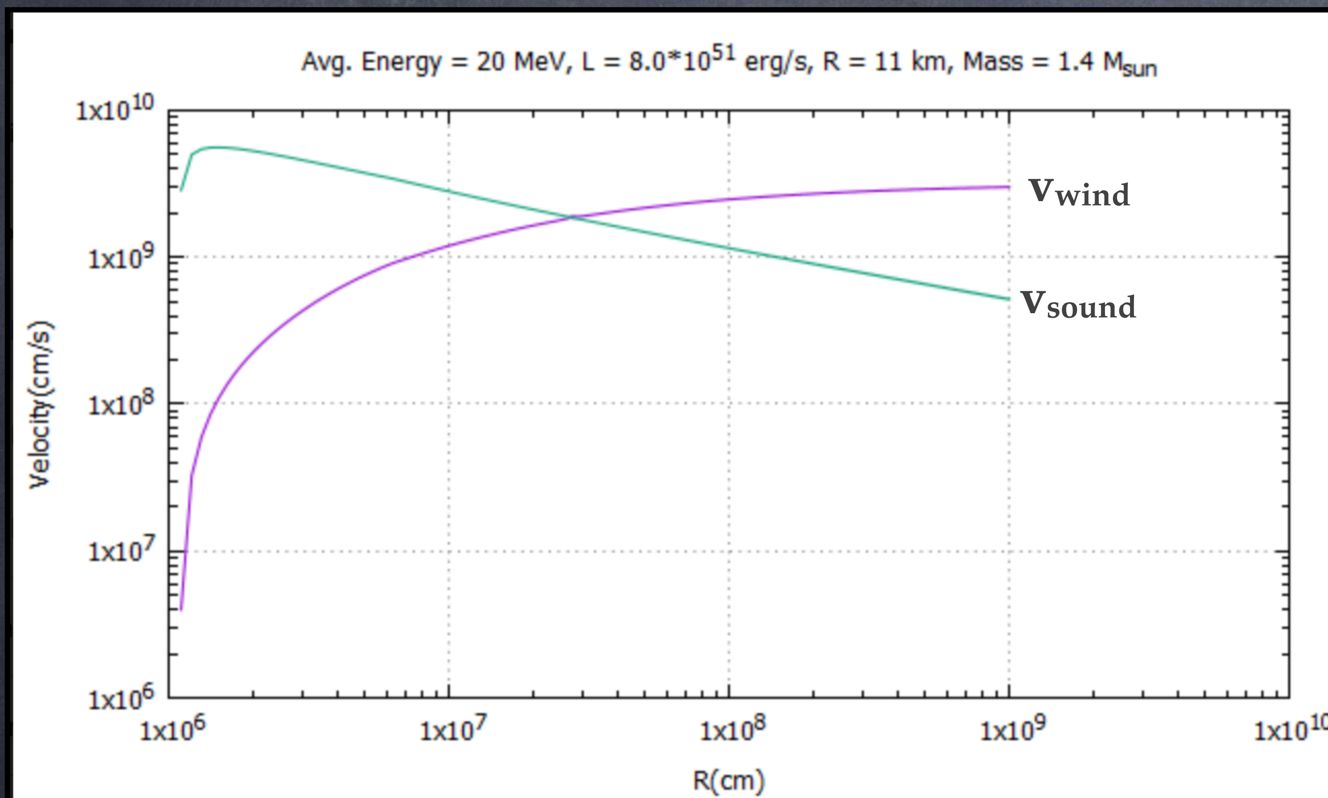
- Entropy is gained in the first 100 km, due to neutrino heating. Typical values are 50-100 per baryon

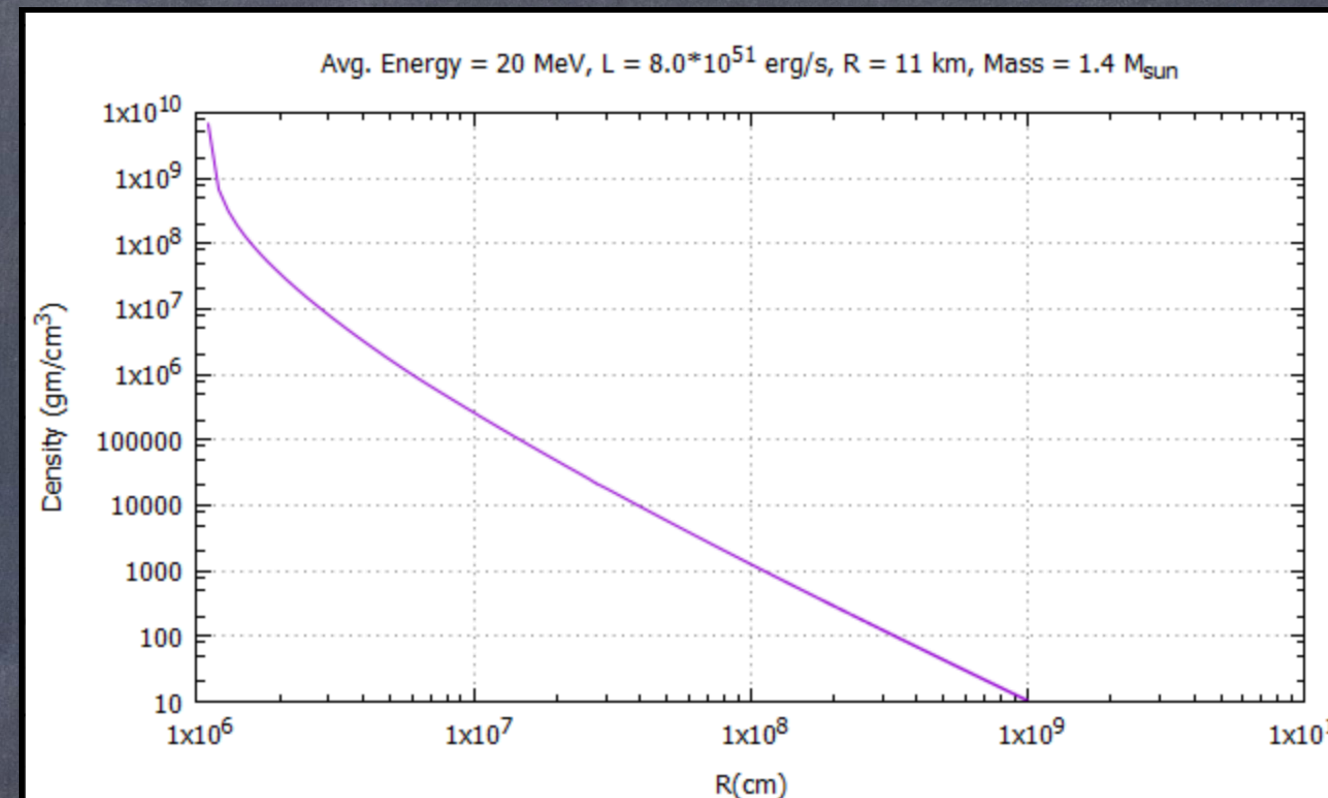


- Outside of the heating region the system simplifies to a single ODE

$$\frac{dv}{dr} = \frac{v}{r}\frac{2v_s^2 - GM/r}{v^2 - v_s^2}$$

Supersonic wind profile





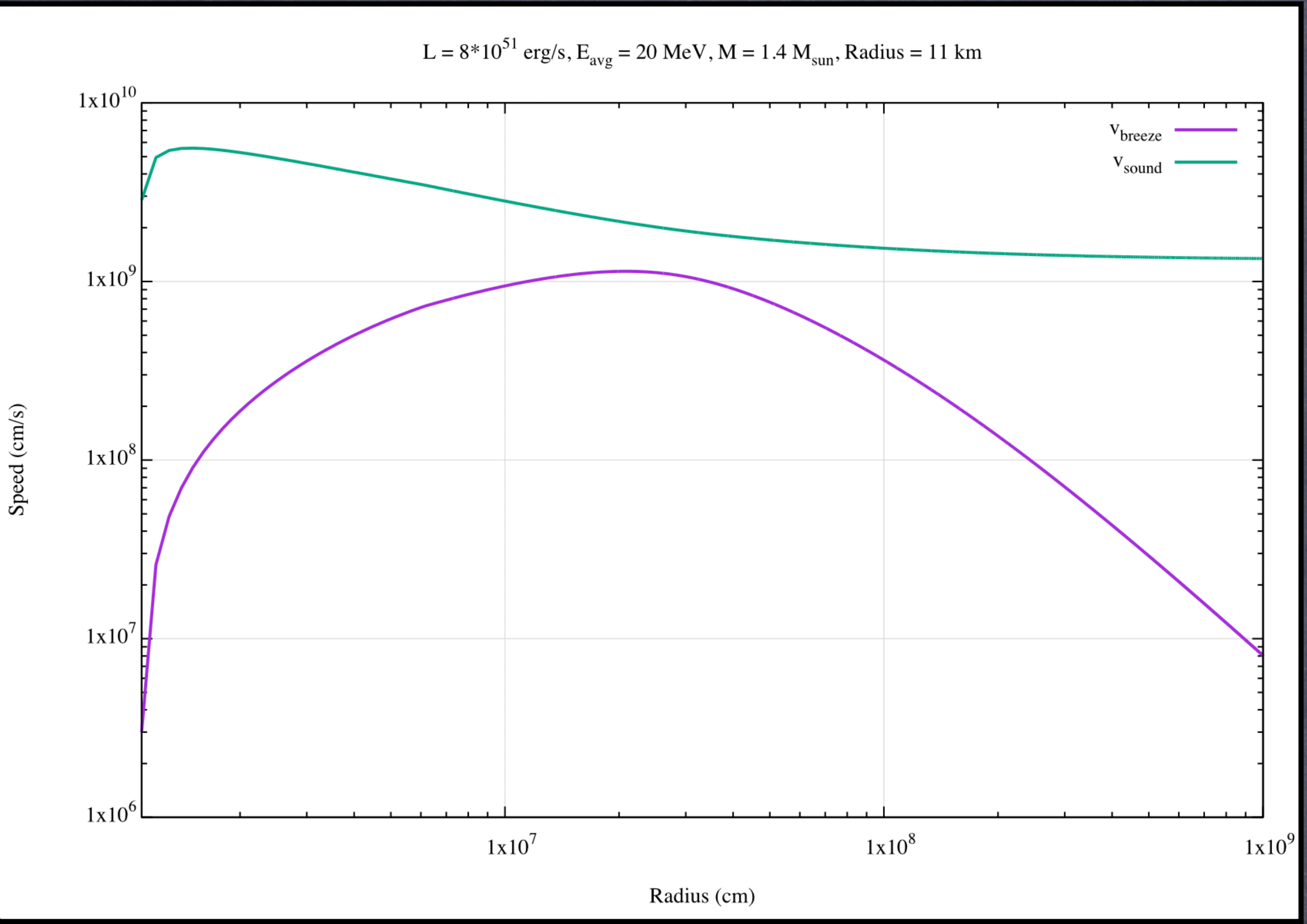
Velocity profile -supersonic flows

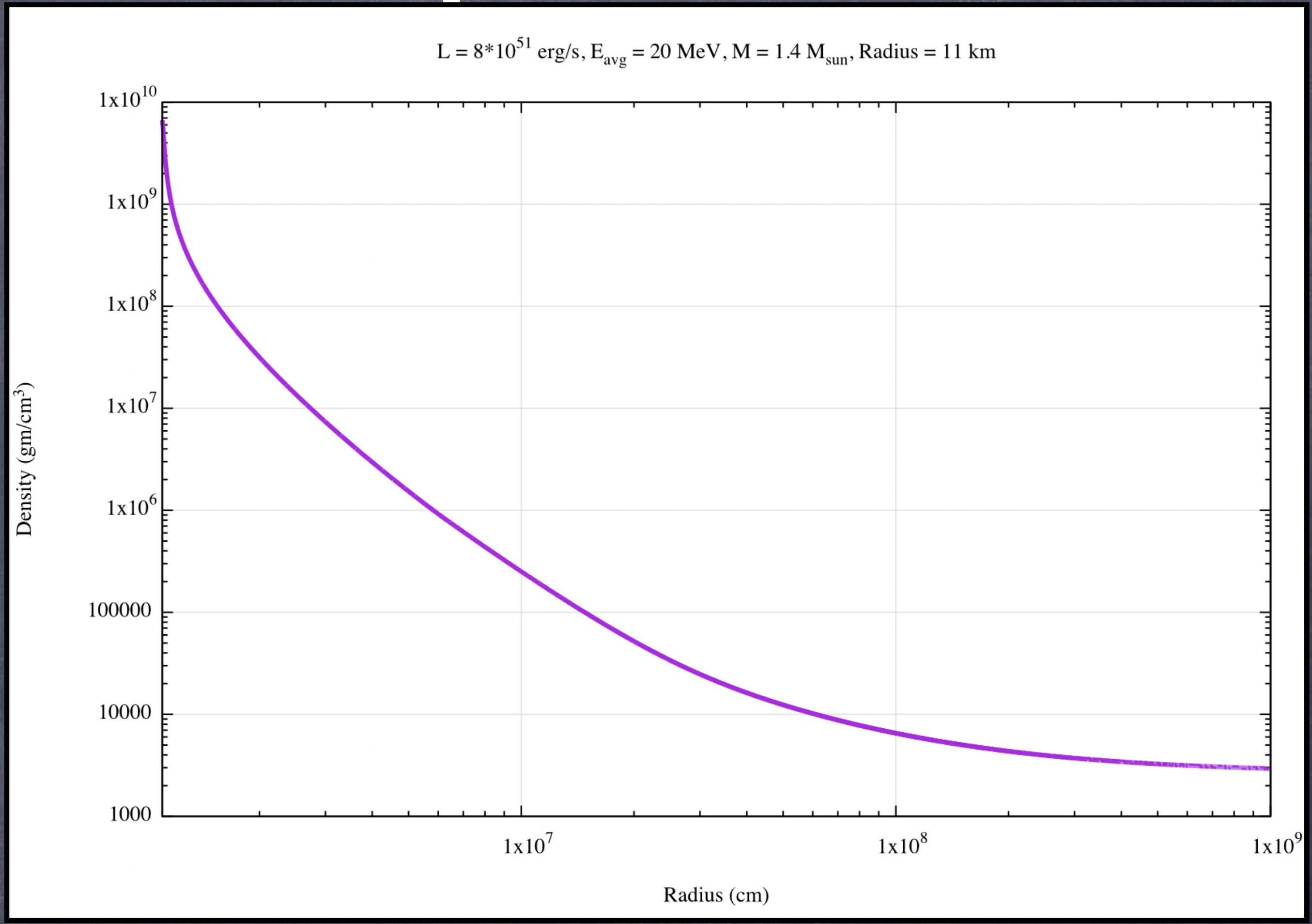
Corresponding density - Expansion into empty space

Qian, Woosley (1996), Thompson, Burrows, Mayer (2001)

In a realistic setup, termination shock. But until the outflow hits the shock, it thinks it's expanding into empty space.

Subsonic breeze profiles



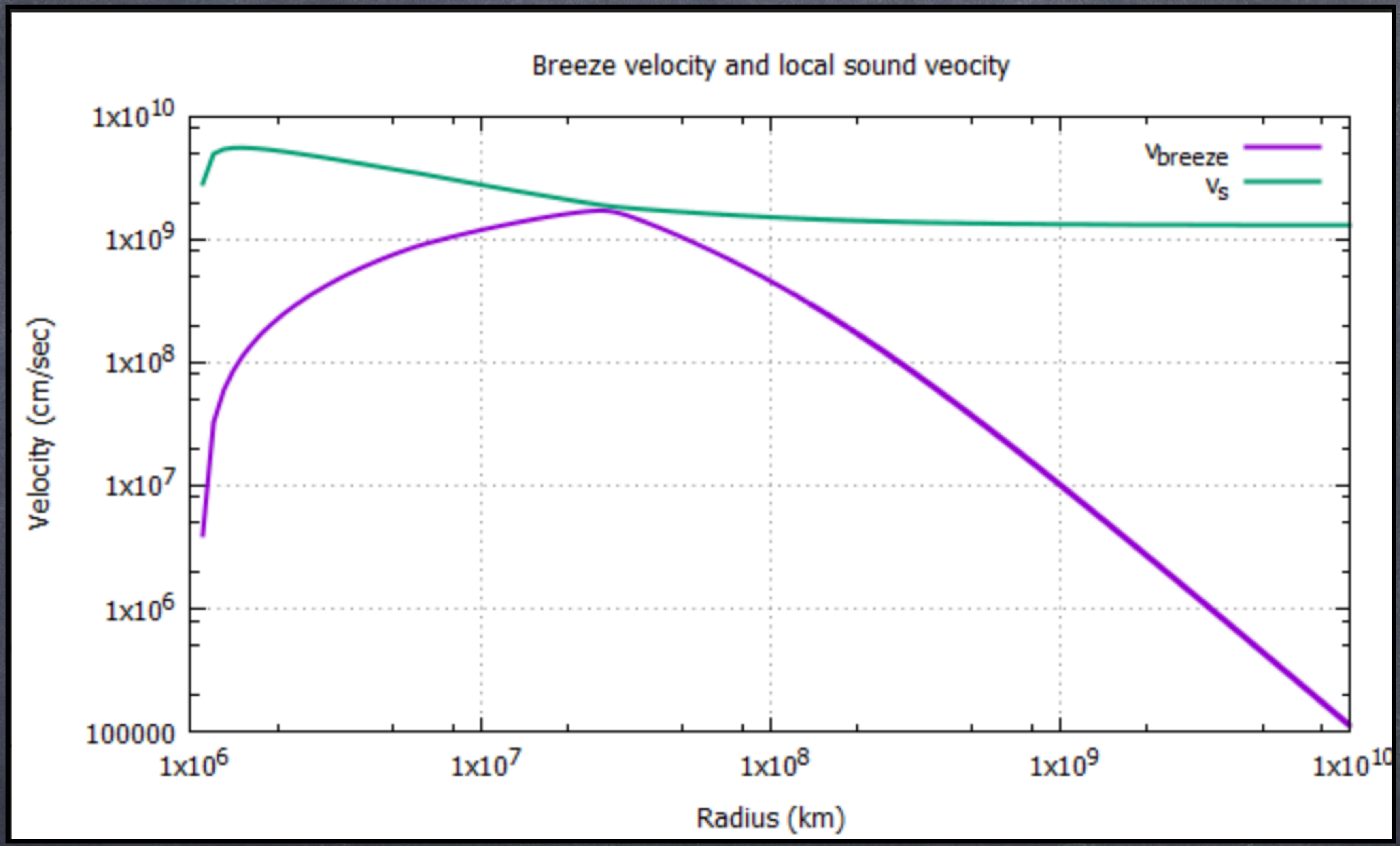


Velocity profile -subsonic flows

Corresponding density - Non-zero density at far end

Everything is causally connected.
The beginning of the wind knows it will flow into a finite-density medium

Critical breeze profile



Critical Breeze velocity curve : Outflow velocity just touches local sound speed at one point.

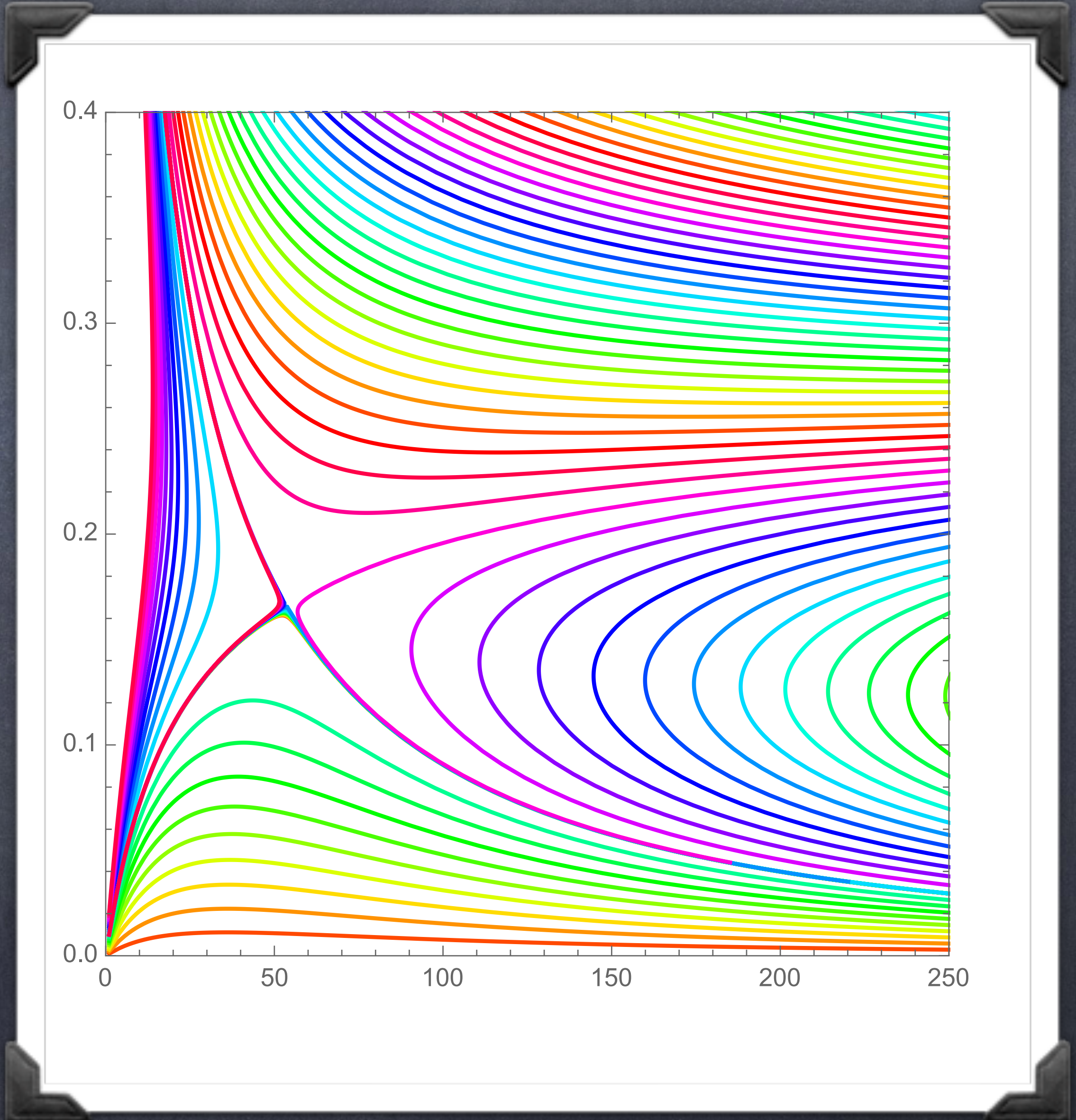
Corresponds to a critical (minimal) far density : $\boldsymbol{\rho}_{crit}$

Notice the kink, suggestive of a phase transition

Phase diagram

$$\frac{dv}{dr} = \frac{v}{r}\frac{2v_s^2 - GM/r}{v^2 - v_s^2}$$

- Simple-looking ODE is non-linear, has a mind of its own
- The sonic point is a critical (saddle) point.
- Below it is a family of subsonic curves, corresponding to various final densities
- The supersonic solution goes through the critical point (unique)



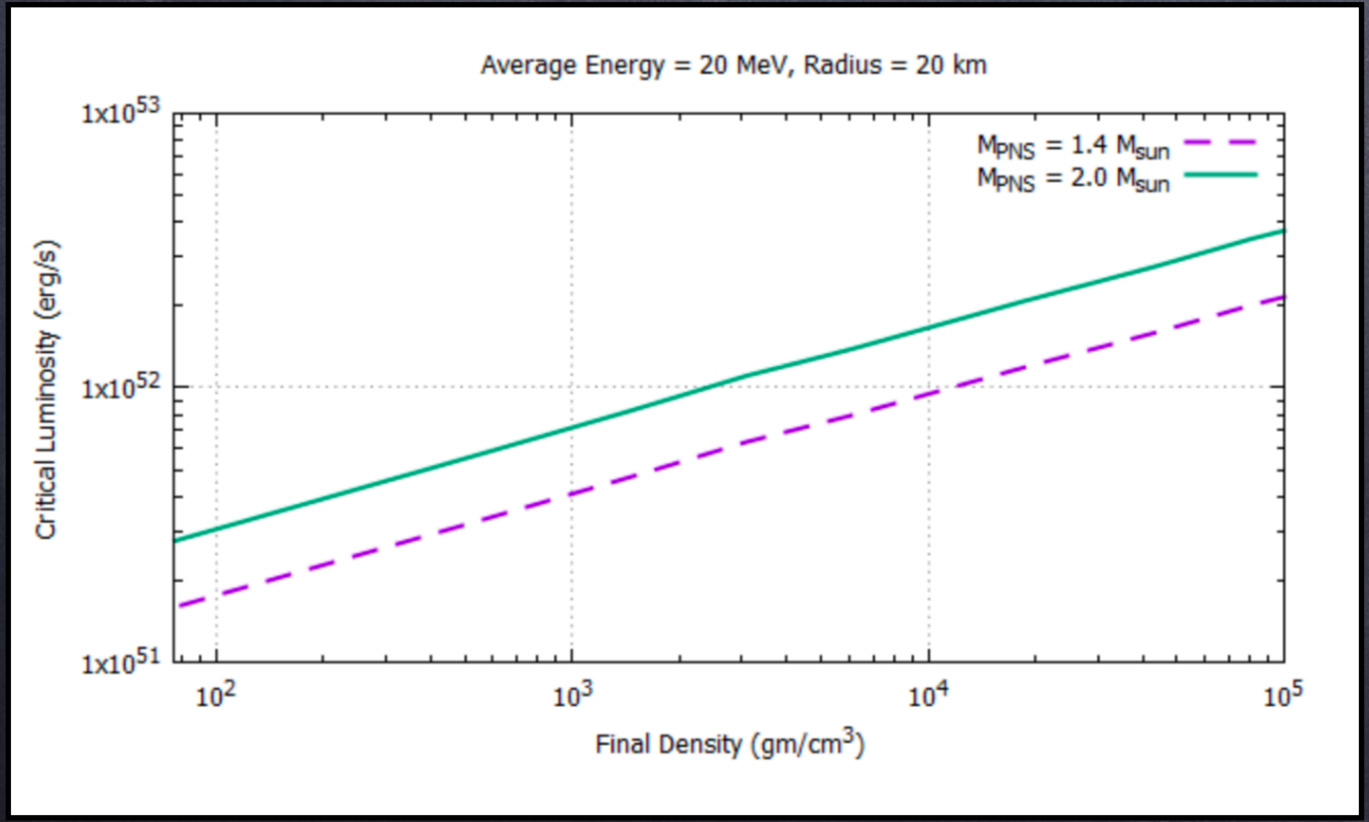
Summary of our findings

- In the space of physical parameters, the boundary between subsonic and supersonic outflows is a phase transition
- We mapped out critical values of basic parameters: neutrino luminosity, average energy, radius and mass of the protoneutron star, and density in the expanding shock
- Turns out, for physical conditions in the realistic explosions, the system is indeed close to critical
- This makes the neutrino signal a very sensitive probe of what exactly happens close to the protoneutron star!

Approximate scaling law for critical density

Numerically

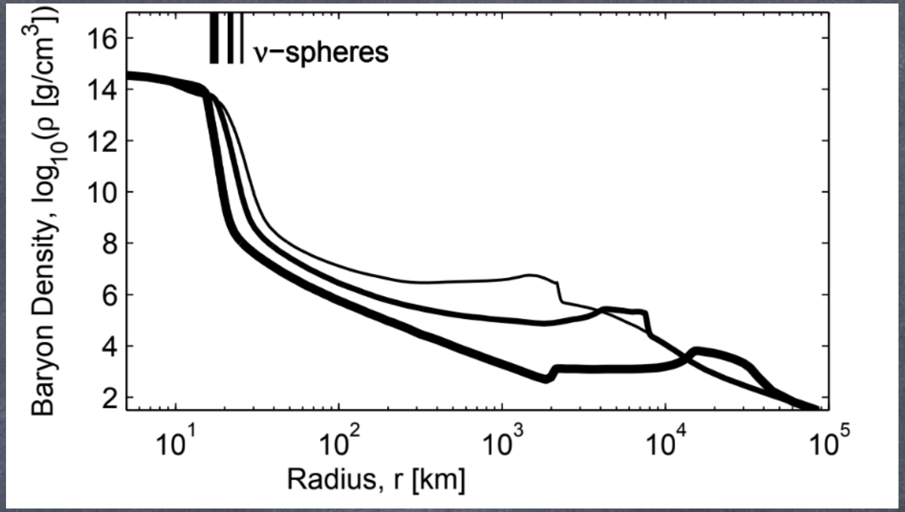
$$\rho_{crit} \propto L^{2.69} R^{0.9} E^{5.1} M^{-4}$$



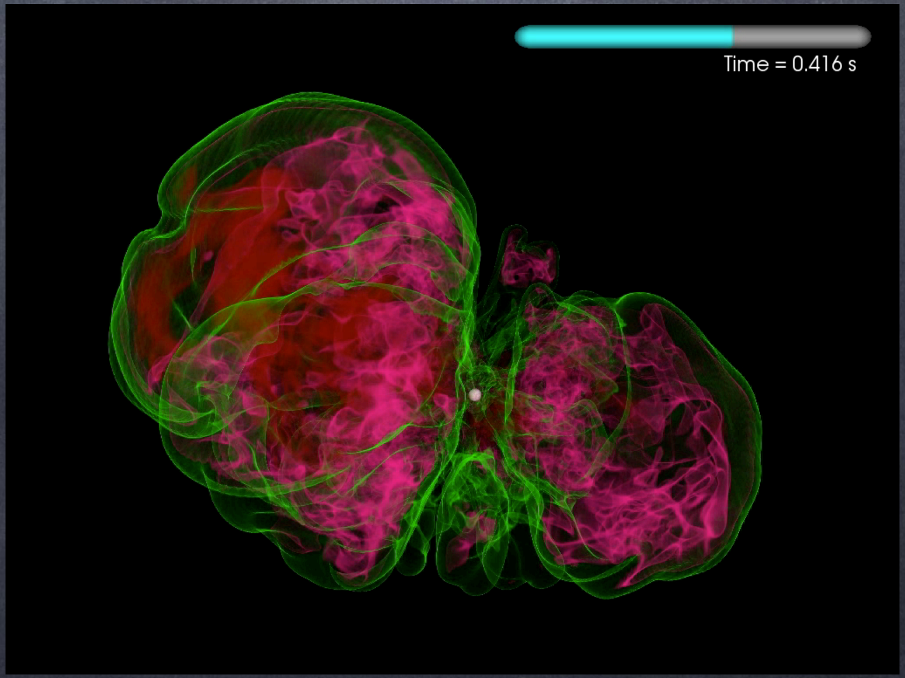
- Example: For L ~ 10^{52} erg/s, the outflow is subsonic when the final density is at least 10^4 gm/cm^3

Our model vs published simulations

- We can reconcile existing simulations: for conditions of Arcones et al (2006), there are indeed strong shocks through the explosion
- For Fisher et al (2009), we indeed find that the outflow changes its character in the first three seconds
- For multi-d simulations, we understand why they don't see shocks. However, if they were to run longer, we predict that shocks may appear for them



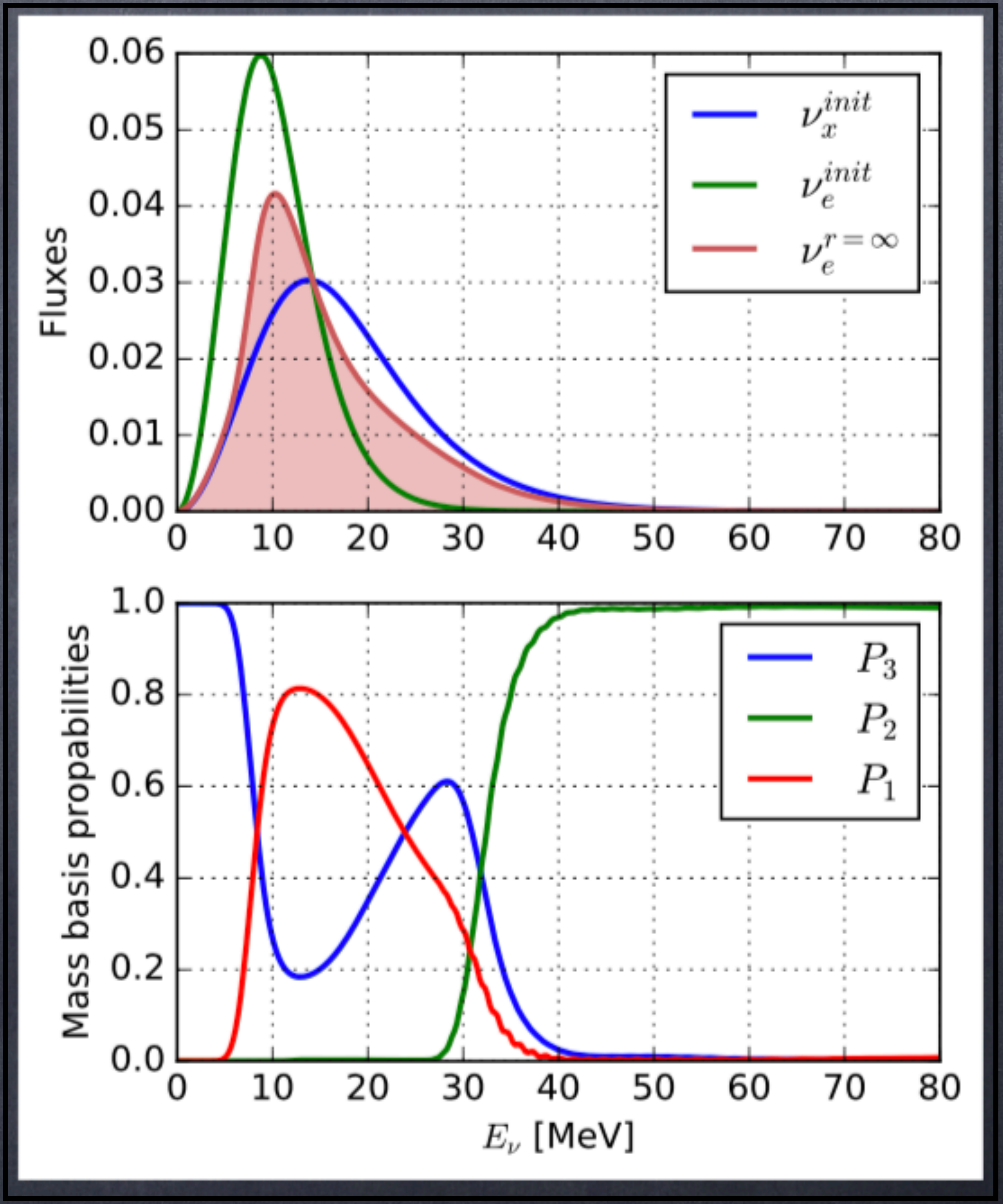
Fischer et al (2009)



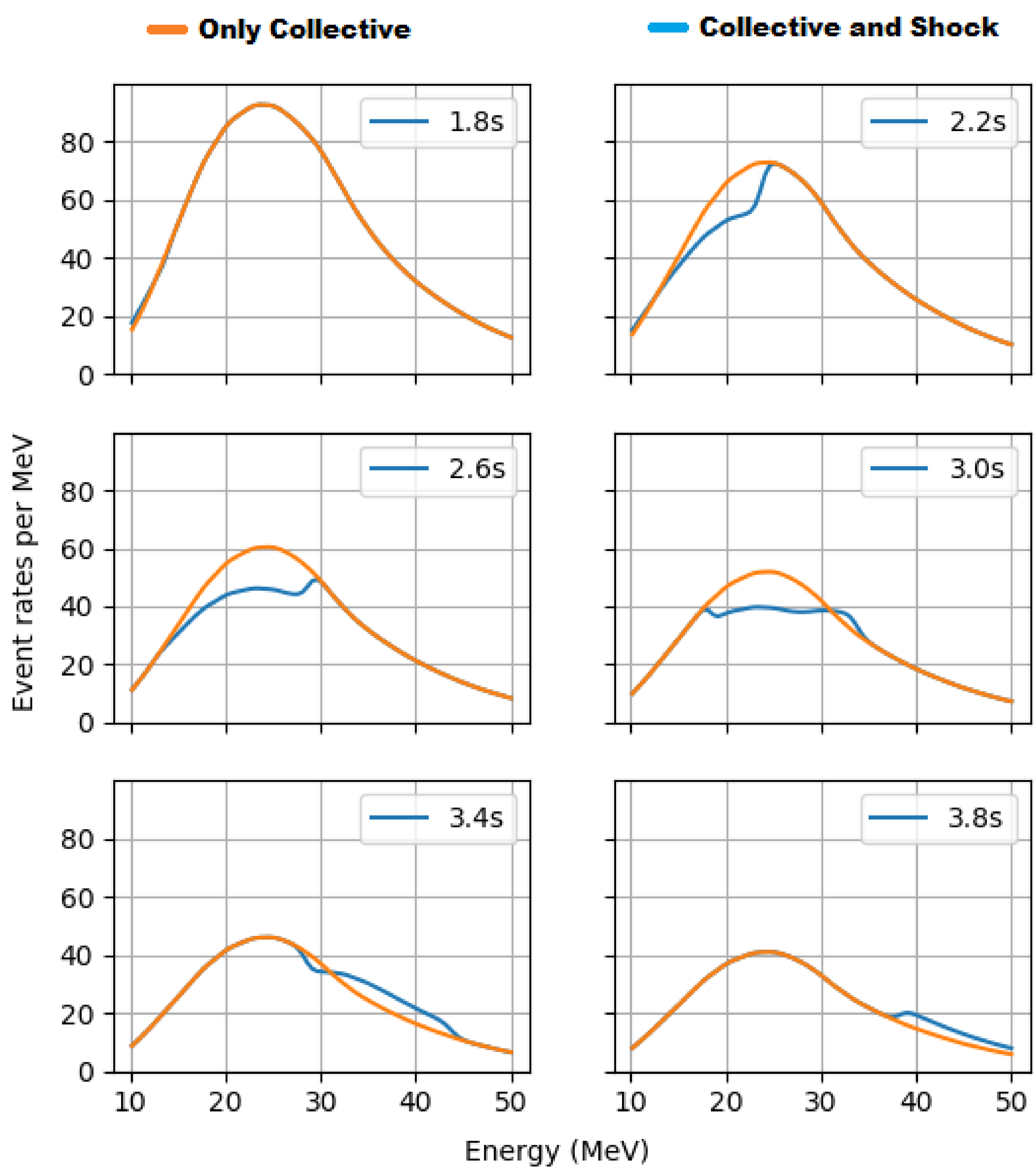
Vartanyan, Burrows, et al (2018)

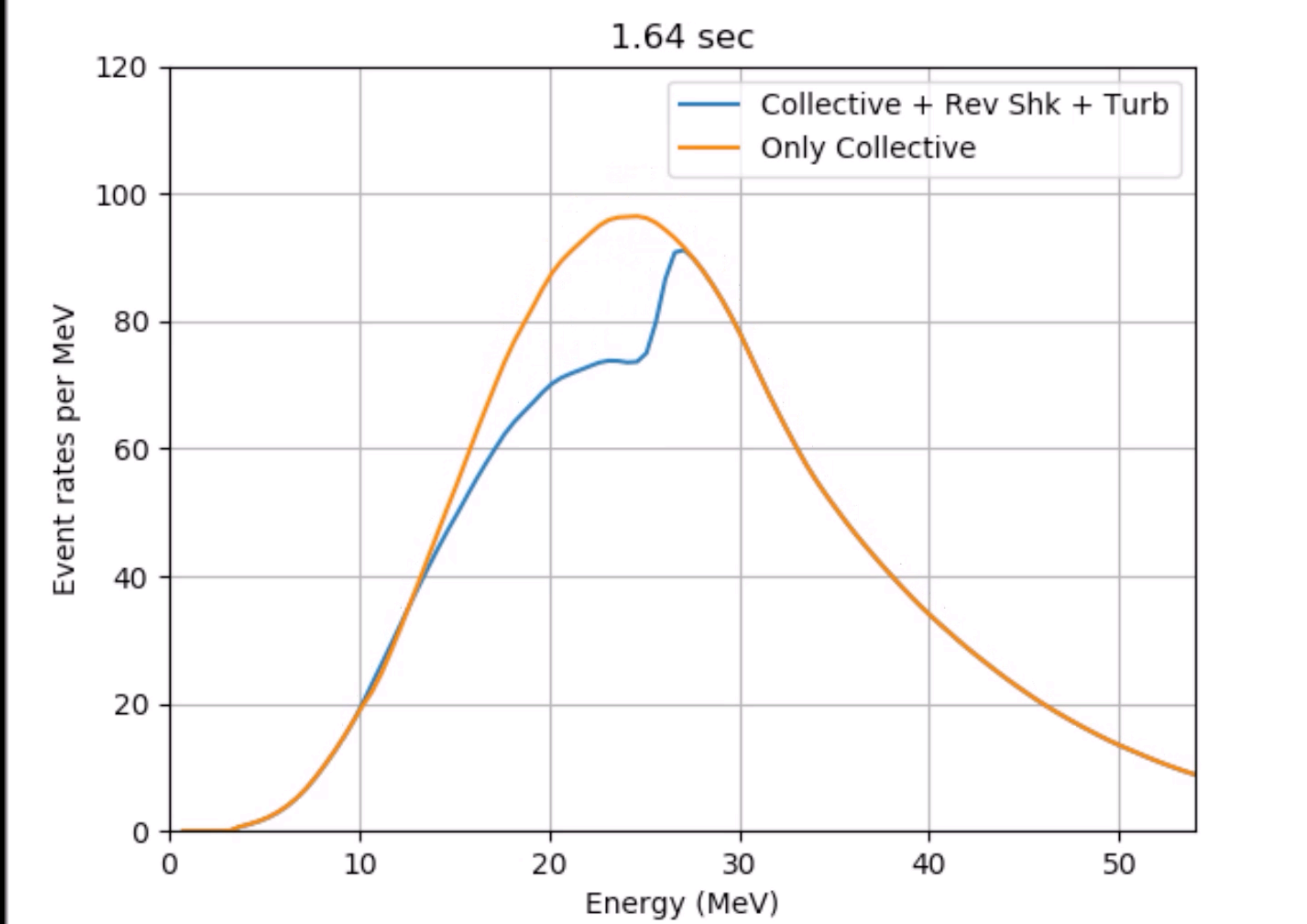
Finally, neutrino signals

- As mentioned, collective oscillations are modeled by our spherically symmetric, multiangle code.
- The result is a spectral split feature that is clearly visible in the mass basis, but not in the flavor basis.
- What happens with shock effects?



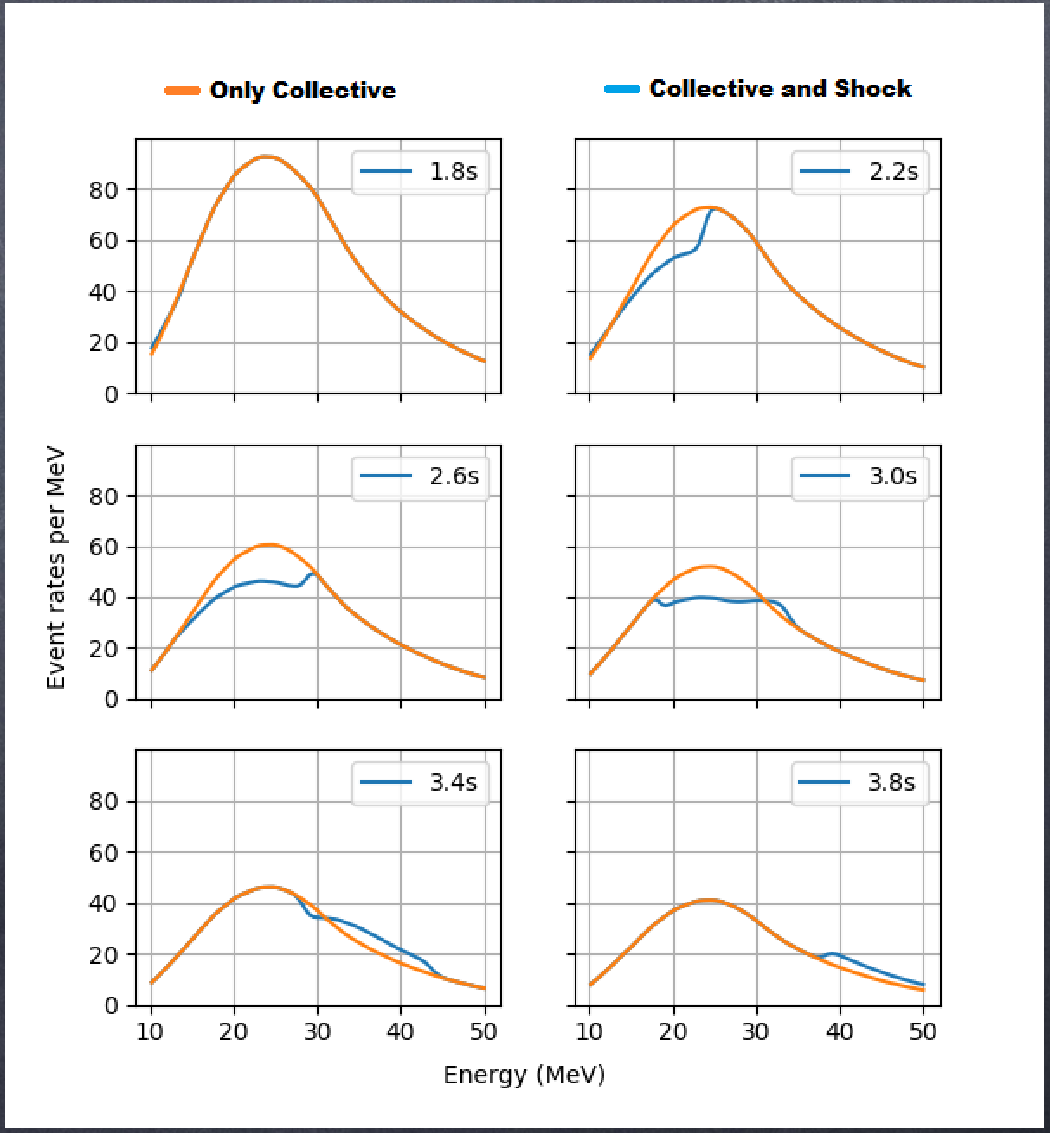
The shock reveals the hidden split ;-)




1.64 sec
Collective + Rev Shk + Turb
Only Collective
Event rates per MeV
Energy (MeV)
0
20
40
60
80
100
120
0
10
20
30
40
50

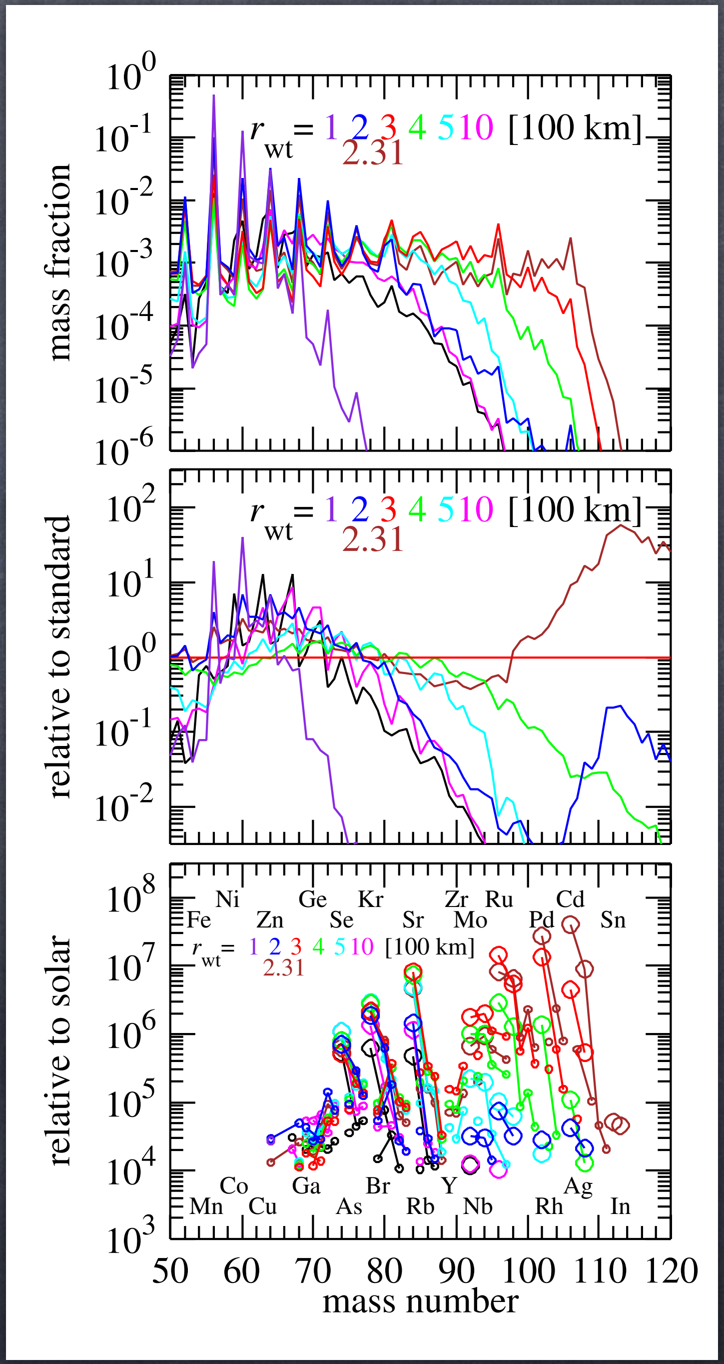
Some comments

- The smoking-gun modulation signal exists only in the neutrino channel -> **Can only be seen at DUNE**
- The moving feature clearly cannot be of thermal origin
- Water is still useful, to monitor antineutrinos, where no features like that are expected due to oscillations



What about nucleosynthesis?

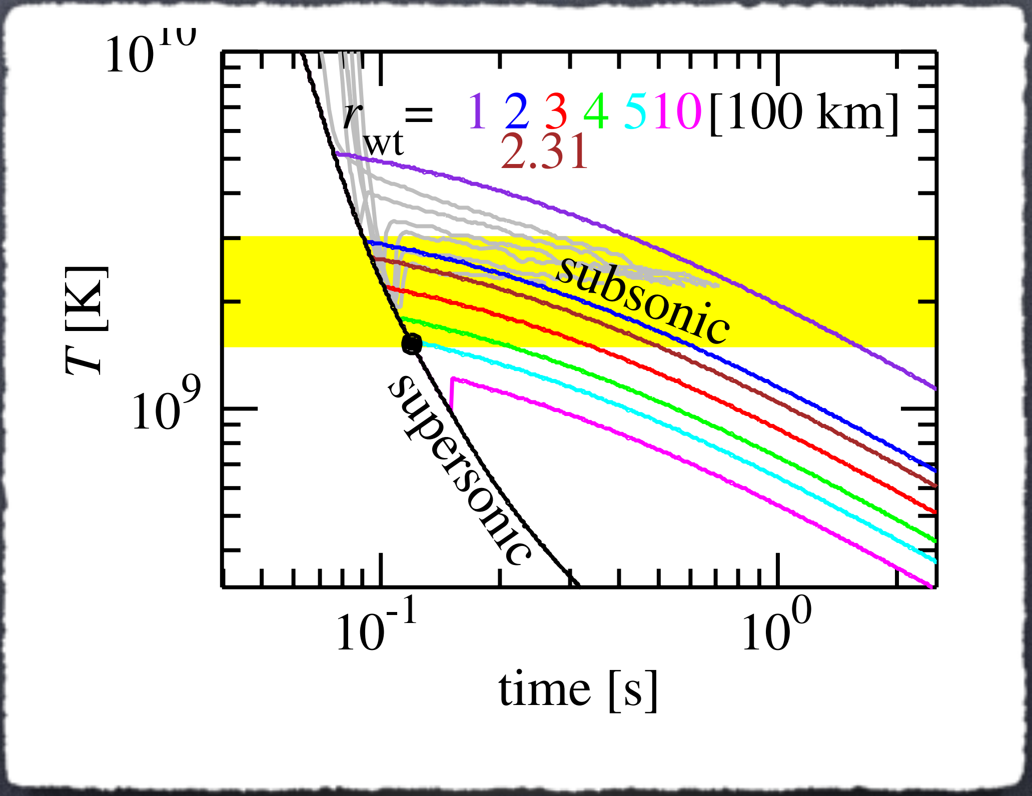
- One would like a systematic study, modeling the impact of wind-to-breeze transition on nucleosynthetic yields. No one has done it yet.
- BUT, people have considered parametric models, where the outflow is modulated "by hand"
- Comparing with our results, we find that our subsonic solution creates **optimal nucleosynthesis conditions** for the $\nu p-$process



Wanajo, Janka, Kubono ApJ (2011)

More details on the nucleosynthesis

- The reactions are called $\nu p-$process.
  - C. Fröhlich et al, astro-ph/0511376
- The only known way to make certain proton-rich isotopes with mass numbers A>64
  - E.g., ^{92,94}Mo and ^{96,98}Ru
  - Requires strong neutrino flux, otherwise stuck on perfect for neutrino-driven outflows ^{64}Ge (half-life 64 s)
- But default simulations using supersonic winds have problems, because the (n,p) reaction on ^{64}Ge has a half-life of 0.25 s at 2 GK. Subsonic flow to the rescue!



Wanajo, Janka, Kubono ApJ (2011)

Summary and outlook

- SNB signal will provide a unique probe of the physical conditions close to the surface of the protoneutron star: it will have imprints of the nature of the high-entropy outflow (neutrino-driven “wind” or “breeze”)
- Assuming normal hierachy, can only be seen at DUNE (nu-e sensitivity)
- The physics of this outflow is different from usual stellar winds: it is on the boundary between subsonic and supersonic
- We systematically mapped out this transition in terms of physical parameters: neutrino luminosities and energies, radius and mass of the PNS
- Subsonic outflows turn out to have ideal conditions to $\nu p-$process nucleosynthesis. Thus, neutrino signal can tell us about conditions for nucleosynthesis.